

Multi-Boson Interactions at the Run 1 LHC

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This review article covers results on the production of all possible electroweak boson pairs and 2-to-1 vector boson fusion (VBF) at the CERN Large Hadron Collider (LHC) in proton-proton collisions at a center-of-mass energy of 7 TeV and 8 TeV. The data was taken between 2010 and 2012. Limits on anomalous triple gauge couplings (aTGCs) then follow. In addition, data on electroweak triple gauge boson production and 2-to-2 vector boson scattering (VBS) yield limits on anomalous quartic gauge boson couplings (aQGCs). The LHC hosts two general purpose experiments, ATLAS and CMS, which both have reported limits on aTGCs and aQGCs which are herein summarized. The interpretation of these limits in terms of an effective field theory (EFT) is reviewed, and recommendations are made for testing other types of new physics using multi-gauge boson production.

CONTENTS

I. Introduction	2	C. $WV\gamma$ Production	21
II. Theory	2	D. $W^\pm W^\pm W^\mp$ Production	22
A. Current Theoretical Understanding of SM cross sections	4	VI. Vector Boson Fusion	22
1. Diboson Production	5	A. Wjj Production	23
2. Vector Boson Scattering and Vector Boson Fusion	6	B. Zjj Production	23
3. Multi-boson Production	6	VII. Vector Boson Scattering	23
B. BSM interplay	6	A. $W^\pm Vjj$ Production	25
1. EFT interpretation of SM measurements	7	B. $W^\pm W^\pm jj$ Production	25
2. Fiducial Cross Sections and BSM recommendations	9	C. $W^\pm Zjj$ Production	26
III. Experimental Setup	10	D. exclusive WW Production	27
IV. Diboson Production	11	VIII. Constraints on anomalous Triple Gauge Couplings	28
A. $\gamma\gamma$ Production	11	A. $WW\gamma$ and WWZ limits	28
B. $W\gamma$ Production	12	B. $Z\gamma\gamma$ and $Z\gamma Z$ limits	29
C. $Z\gamma$ Production	13	C. $ZZ\gamma$ and ZZZ limits	29
D. W^+W^- Production	14	IX. Constraints on anomalous Quartic Gauge Couplings	30
E. $W^\pm V$ Production	16	X. Sensitivity prospects at the HL-LHC	33
F. ZV Production	16	XI. Conclusions	37
G. $W^\pm Z$ Production	17	XII. Acknowledgments	37
H. ZZ Production	17	References	40
V. Triboson Production	19		
A. $W\gamma\gamma$ Production	19		
B. $Z\gamma\gamma$ Production	20		

I. INTRODUCTION

The Standard Model (SM) of particle physics is based on the $SU(3)_C \otimes SU(2)_L \otimes U(1)_Y$ gauge symmetry group and describes the interactions among all the elementary particles. With the discovery of a light Higgs boson, the SM is a complete and self-consistent theory which can and should be tested as closely as possible.

Because the electroweak gauge bosons carry weak charge the SM predicts interaction vertices which contain three bosons (triple gauge coupling) or four bosons (quartic gauge coupling). Because of these interactions, the inclusive production of pairs and triplets of gauge bosons is expected in the SM.

Previous experiments have studied the production of pairs of gauge bosons. The LEP experiments studied WW and WZ production as a function of center of mass (C.M.) energy. Indeed, the triple vertices were found to be critical in limiting the growth of the cross sections with energy giving strong confirmation of the correctness of the SM. Limits were set by the LEP experiments on anomalous triple gauge couplings (aTGCs) for the first time and these limits (Schael *et al.*, 2013) have remained the most stringent until the advent of the Large Hadron Collider (LHC) at CERN.

Experiments at the Tevatron (CDF and D0) also measured exclusive gauge pair production extending the data on final states to WW , WZ , ZZ , $W\gamma$, $Z\gamma$ and $\gamma\gamma$. In these final states the dynamics of the process, especially at large diboson C.M. energy could be used to further test the predictions of the SM. For a recent review of the relevant Tevatron results, the reader is referred to (Kotwal *et al.*, 2015).

The LHC experiments ATLAS and CMS have begun to exploit the increased C.M. energy of the LHC and the associated large increase in cross section to expand the gauge coupling studies. In particular, the energy at the triple and quartic vertices has been pushed into the TeV range. As the energy and luminosity of the LHC continue to increase, ever more incisive studies will open up.

This review covers the LHC proton-proton data taking up to the end of 2012, which occurred at 7 and 8 TeV. The diboson states herein covered consist of all gauge boson pairs, $\gamma\gamma$, $W\gamma$, $Z\gamma$, WW , WZ and ZZ . In each case limits on aTGCs could be set and they have now surpassed the previous LEP and Tevatron limits. A unique feature of the LHC data is the first exploration of triple gauge boson production with $W\gamma\gamma$, $Z\gamma\gamma$ and WWW final states, summarized in this review. The corresponding first limits on aQGCs which have been reported are herein summarized.

A second set of limits on aQGC arise from the studies of exclusive final states in the Vector Boson Scattering (VBS) topology. In that case the initial proton - proton state, due to the virtual emission of two gauge bosons, contains two remnant, forward going jets and a more

centrally produced final state with the resulting VBS dibosons. In this review, aQGC limits are derived for the VBS states, $WVjj$, $W^\pm W^\pm jj$, $WZjj$ and $\gamma\gamma \rightarrow WW$, where the symbol j refers to the remnant jet. In the particular case where the protons emit soft photons in the VBS initial state ($\gamma\gamma \rightarrow VV$), remnant jets are not part of the VBS signature.

This article is organized as follows. In Section II the theory of multi-gauge boson interactions in the SM and the modern treatment of deviations being described by an EFT is reviewed. Additionally, the impact of multi-gauge boson physics beyond simple shifts in aTGC an aQGC measurements is emphasized, and a model independent recommendation for experiments is made. In Section III a brief description of the relevant experimental issues is defined and references are given for the relevant experimental aspects of the ATLAS and CMS experiments. In Section IV the published LHC diboson studies are presented while in Section V the triboson results are shown. In Section VI the vector boson fusion data for W and Z bosons are shown as a proof of principle that this electroweak process can be extracted from the experimental backgrounds. Armed with those analyses, the data on VBS is presented in Section VII. The existing limits on gauge couplings are collected in Section VIII for aTGC and IX for aQGC. Finally, Section X explores the prospects for gauge coupling studies with the increased luminosity planned for the LHC as set out by CERN.

II. THEORY

There are a variety of theoretical motivations for testing the structure of multi-boson interactions at the LHC. Given the non-Abelian nature of the ElectroWeak (EW) sector of the SM, this allows one to test non-Abelian gauge theories directly. While this of course had already been done in other ways with QCD, the weakly coupled non-confining nature of the EW gauge symmetry allows for the investigation of this in unprecedented detail at higher energies and with more luminosity. However, what is even more important is the connection between the study of multiple EW gauge bosons and the structure of EWSB.

The W^\pm , Z and γ , through mixing, represent the sector of the SM most strongly coupled to EWSB other than the top quark. Since the discovery by ATLAS (Aad *et al.*, 2012i) and CMS (Chatrchyan *et al.*, 2012b) of a Higgs boson, we have definitive proof that the ultimate mechanism of EWSB must look very much like the simple ad hoc Higgs Mechanism. However, this of course results in many more theoretical problems than answers. In particular the appearance of spontaneous symmetry breaking without a dynamical origin associated to a scalar field brings the hierarchy problem to the fore. Given that EW gauge bosons offer a relatively clean signal at the LHC, if

there is *any* structure to EWSB beyond the Higgs this is clearly one of, if not the best ways to go about searching for it.

Both the non-Abelian nature of EW gauge bosons and their connection to EWSB have been utilized in past phenomenological studies that have spurred decades long experimental programs at many different colliders. Historically these two threads, EWSB and non-Abelian couplings were studied independently despite their intertwined nature.

The origin of testing the non-Abelian structure through EW gauge bosons typically goes back to (Hagiwara *et al.*, 1987). In that paper a parametrization of possible triple gauge boson couplings consistent with Lorentz invariance and charge conservation was given

$$\begin{aligned} \mathcal{L}_{WWV} = & ig_1^V (W_{\mu\nu}^\dagger W^\mu V^\nu - W_\mu^\dagger V_\nu W^{\mu\nu}) \\ & + \frac{i\lambda_V}{m_W^2} W_{\lambda\mu}^\dagger W_\nu^\mu V^{\nu\lambda} - g_4^V W_\mu^\dagger W_\nu (\partial^\mu V^\nu + \partial^\nu V^\mu) \\ & + g_5^V \epsilon^{\mu\nu\rho\sigma} \left(W_\mu^\dagger \overset{\leftrightarrow}{\partial} W_\nu \right) V_\sigma + i\tilde{\kappa}_V W_\mu^\dagger W_\nu \tilde{V}^{\mu\nu} \\ & + \frac{i\tilde{\lambda}_V}{m_W^2} W_{\lambda\mu}^\dagger W_\nu^\mu \tilde{V}^{\nu\lambda} + i\kappa_V W_\mu^\dagger W_\nu V^{\mu\nu}, \end{aligned} \quad (1)$$

where W^μ is the W^- , V represented either the Z or γ , the two-index V or W tensors are Abelian field strengths, and \tilde{V} is the result of contracting two indices with the 4-index epsilon tensor. Historically, this was a very relevant parametrization since this was before LEP II, and as such pair production of W bosons had yet to be studied experimentally. Therefore in principle, there could have been large deviations as the non-Abelian structure of the EW gauge bosons had not yet been directly probed. Once energies sufficient to produce dibosons was achieved, the effective Lagrangian (1) could lead to deviations in processes such as those shown in Figure 1 or there could be constraints placed on the various couplings.

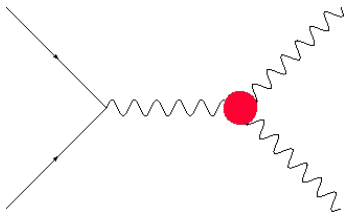


FIG. 1 Diboson production via Drell-Yan at a lepton or hadron collider. The red insertion represents using a term from the parametrized Lagrangian in (1).

This parametrization was then carried forward and has been used as the basis for experimental studies of aTGCs for approximately the last three decades.

The historical connection between multiple vector boson production and EWSB is the role of the Higgs in unitarizing vector boson scattering (VBS) (Chanowitz and Gaillard, 1985; Cornwall *et al.*, 1973, 1974; Dicus and

Mathur, 1973; Lee *et al.*, 1977; Llewellyn Smith, 1973). Well before the discovery of the Higgs, it was known that the scattering of massive vector bosons without a Higgs-like state have amplitudes that grow as $\sim E^2$. Naively, if the SM EW gauge bosons were scattered at energies $\sim 4\pi m_W/g$ tree-level unitarity would appear to be violated. Of course this did not mean that unitarity actually would have been violated, it simply meant that the theory of EWSB and massive gauge bosons would become strongly coupled and unpredictable at these scales. If the Higgs existed, the growth with energy would have been canceled by the Higgs contribution, and perturbative unitarity would have been manifest and calculable within this framework. To test VBS, the simplest process one can study experimentally is shown in Figure 2. However, sim-

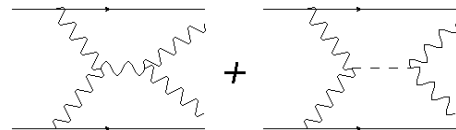


FIG. 2 VBS in the SM with the exchange of gauge bosons on the LHS and the Higgs on the RHS needed to preserve perturbative unitarity in the SM.

ilarly to the case of aTGCs, when the role of using VBS to test EWSB was first proposed, the Higgs had never been seen, in fact almost four decades would pass before its discovery. At that point there were promising alternatives to the ad hoc Higgs mechanism which could explain EWSB dynamically, such as Technicolor (Farhi and Susskind, 1981) and composite Higgs models (Kaplan and Georgi, 1984). In these models unitarity wasn't violated either, instead of the Higgs, additional massive states responsible for restoring perturbative unitarity that couple to our gauge bosons would appear in the RHS diagram of Figure 2. A similar way of studying this, if the energy of the collider can not directly produce the new states responsible for perturbative unitarity, is again through anomalous couplings. For instance, if one introduces both aTGCs as in (1) and anomalous quartic gauge bosons couplings (aQGCs) as shown in Figure 3, both will have effects on VBS measurements. Regardless of how deviations from

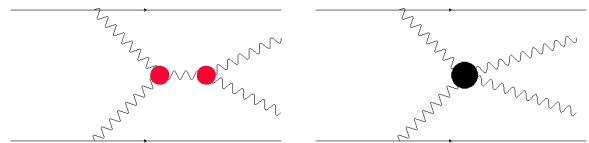


FIG. 3 Examples of Vector Boson Scattering (VBS) contributions from aTGCs and aQGCs.

new sources of EWSB are parametrized, the connection between EWSB and VBS has been viewed as a window into the nature of EWSB since the early days of planning for the SSC (Chanowitz and Gaillard, 1985). Since the discovery of a Higgs-like state, the direct connection to

perturbative unitarity studies has been reduced, nevertheless it will be an important validation of the SM to show the effects of the Higgs on vector boson scattering at the LHC. Additionally, there could still be small deviations in the EWSB that would manifest themselves in VBF or VBS either as more obvious deviations in the differential cross section or in searches for aTGCs or aQGCs in these channels.

These two independent threads, testing non-Abelian gauge boson couplings and unitarity of massive vector boson scattering were both originally very well motivated in their search for large deviations in the EW sector. However, with the advancement of knowledge from LEP, the Tevatron and the LHC it is important to understand their failings in our modern day understanding of the SM including the Higgs. In Section II.B we will review the breakdown of historical methods for studying multiple production of EW gauge bosons that are still propagated today, including in the experimental sections of this review. We will also discuss how attempts to improve on testing for deviations in coupling constants have been done through EFT methods. This is a useful tool to understand where to look for deviations in experimental results and how to parametrize them, but only if used correctly. We will attempt to delineate these efforts both theoretically and experimentally as there are failings on both sides with respect to the application of EFTs for multi-gauge boson production. Finally, in Section II.B.2 we discuss the important role of multi-gauge boson production in searches for BSM physics which have no connection to EFTs whatsoever. This is an important and often overlooked or factorized result given the structure of ATLAS and CMS. Nevertheless, the relation massive gauge bosons have to EWSB dictates that this is as important as any other topic reviewed.

To make any connection to BSM physics using multiple production of EW gauge bosons requires a precise understanding of the theoretical predictions for the SM. There has been rapid progress in this field over the past few years, notably several new NNLO calculations have become available. Simultaneously the LHC has entered into an era where there are sufficient statistics in multiple gauge boson production channels that NNLO and higher order corrections have started to become required to explain the data sufficiently. In addition, to go beyond the first implications of the Higgs and delve into possibilities for EWSB, the Higgs itself has become inextricably intertwined in current and future predictions for the LHC. Therefore before turning to BSM possibilities we will briefly review in Section II.A the current theoretical understanding of SM predictions for multiple EW gauge boson production.

A. Current Theoretical Understanding of SM cross sections

The precision of theoretical calculations over the past decade has grown by leaps and bounds, and in particular in the last few years. Prior to the LHC, the state of the art for many calculations was Next to Leading Order (NLO) in α_s , and even that was not fully developed. In particular, in 2005 there was an "experimentalists NLO wishlist" developed at Les Houches (Buttar *et al.*, 2006) for many processes relevant for the LHC. Since 2005, this wishlist has essentially been completed, and now MC programs are available to calculate at NLO in QCD automatically. This amazing progress of course has been matched experimentally by the exquisite measurements done at the LHC combined with the copious statistics that continue to accumulate. This has necessitated at least three important new developments from theory.

The first is simply improving the theoretical precision of inclusive cross sections from NLO to NNLO in α_s and of course ultimately reaching this accuracy in fully differential cross sections as well. There has been much progress on this front that we will discuss further in the next subsection. Improving in α_s also can introduce new production channels as well. At lowest order all processes that we discuss in this review are quark initiated production, however, for instance at NNLO in α_s , $pp \rightarrow VV$ includes both $q\bar{q} \rightarrow VV$ and $gg \rightarrow VV$. This implies that when reaching NNLO accuracy defined for the quark initiated process we have only reached LO in gluon initiated processes. Therefore it is also important to advance on NLO for gluon initiated process to learn the size of the first correction. There is some recent progress on this that we will also discuss for the channels where it has been calculated.

The second development necessary is the inclusion of NLO EW corrections. If we parametrize the cross section as going from LO to higher in powers of α_W and α_s (keeping in mind the caveat of new channels at higher order) as

$$d\sigma \sim d\sigma_{LO} \left(1 + \sum_i \alpha_s^i d\sigma_{N^i LO} + \sum_i \alpha_W^i d\sigma_{N^i LO_{EW}} + \text{mixed corrections} \right), \quad (2)$$

reaching NNLO QCD accuracy parametrically implies needing NLO EW as well, since at the EW scale $\alpha_s^2 \sim \alpha_W$. This of course is just a rough estimate, as there are many other factors that enter in other than the coupling constant. However, the structure of EW corrections, especially in the high invariant mass/high p_T regions typically has the opposite sign compared to QCD corrections and as such is very important to correctly search for new physics.

The third is due to the nature of the measurements per-

formed at the LHC. In attempting to isolate multiboson processes, one has to deal with many QCD background processes. Reducing the QCD background by exclusively looking in the 0-jet final state of a leptonic diboson final state is experimentally advantageous. However, this introduces a new scale into the problem which is typically quite disparate from the hard scale. The existence of two very different scales requires one to resum the large logarithms which arise to make accurate predictions.

In the following subsections we outline the current status of theoretical calculations for three distinct types of processes at the LHC. First, we discuss the inclusive diboson final state, whose large cross sections and potentially clean final states can provide a standard candle for many measurements and searches at the LHC. We then discuss the exclusive VBF/VBS final states which represent a subset of the kinematics for inclusive single or diboson production. Finally, we briefly discuss the theoretical status of multiboson production where multi means greater than two. These are new measurements that go beyond previous colliders and will become more important with the HL-LHC run, both as a signal in and of itself and a background to searches. For a more complete status of SM theoretical calculations beyond those for multi-boson production we refer the reader to (Andersen *et al.*, 2016) and (Campanario *et al.*, 2015). We also note that there are a number of multipurpose event generators used for the various multiboson processes, such as VBFNLO (Arnold *et al.*, 2009, 2011; Baglio *et al.*, 2014), MadGraph5_aMCNLO (Alwall *et al.*, 2014), Powheg Box (Alioli *et al.*, 2010; Frixione *et al.*, 2007; Melia *et al.*, 2011; Nason, 2004; Nason and Zanderighi, 2014), Sherpa (Gleisberg *et al.*, 2009; Gleisberg and Höche, 2008; Höche *et al.*, 2009; Schumann and Krauss, 2008), and MCFM (Boughezal *et al.*, 2016; Campbell and Ellis, 1999; Campbell *et al.*, 2015, 2011b). In the subsections below we concentrate on the current status of theoretical calculations rather than comparing the different MC capabilities.

1. Diboson Production

For diboson production the state of the art QCD calculation is NNLO for W^+W^- (Gehrmann *et al.*, 2014; Grazzini *et al.*, 2016a), $W^\pm\gamma$ (Denner *et al.*, 2015; Grazzini *et al.*, 2015a), $W^\pm Z$ (Grazzini *et al.*, 2016b), ZZ (Casoli *et al.*, 2014; Grazzini *et al.*, 2015b), $Z\gamma$ (Denner *et al.*, 2016; Grazzini *et al.*, 2015a) and $\gamma\gamma$ (Campbell *et al.*, 2016). There has been recent rapid progress on this front using q_T subtraction techniques and in the near future public codes will hopefully be available to automate event generation such as MATRIX (Wiesemann *et al.*, 2016). To get to this accuracy VV' with up to two additional jets has also been calculated to NLO accuracy in QCD. Additionally it will be important to understand

how to combine NNLO cross sections with parton showers to come up with fully differential events (Alioli *et al.*, 2014). On the α_s frontier it is important to also push $gg \rightarrow VV$ to NLO because when computing formally at NNLO this is only the lowest order process. Recently there has been progress in this, with $gg \rightarrow W^+W^-$ being calculated at NLO in (Caola *et al.*, 2016) and $gg \rightarrow ZZ$ being calculated in (Caola *et al.*, 2015). Finally, the matching of NLO gluon initiated processes to a parton shower must also be included, and was recently done for ZZ in (Alioli *et al.*, 2016).

The NLO EW corrections have also been computed for a subset of the processes for which the NNLO QCD corrections are known. For ZZ production including decay, the NLO EW corrections were calculated in (Biedermann *et al.*, 2016a). For the case of W^+W^- this was carried out in (Biedermann *et al.*, 2016b). The $Z\gamma$ and $W\gamma$ processes were calculated at the NLO EW order in (Denner *et al.*, 2016) and (Denner *et al.*, 2015). In the case of $W\gamma$ and $Z\gamma$ this was done in combination with the NLO QCD corrections. The next frontier is to calculate jointly to NNLO in QCD and NLO in EW as well as for the decays.

For diboson production, once NNLO in α_s is reached, there also is the possibility to evaluate the interference between $gg \rightarrow VV$ and $gg \rightarrow H \rightarrow VV$. This has been pointed out and calculated in (Campbell *et al.*, 2011a) where a non-negligible effect was demonstrated.

There also are various different types of resummation that have been carried out for diboson production such as threshold resummation, p_T resummation, and jet-veto resummation in certain cases. Threshold resummation can give a good approximation for higher order calculations, for instance the W^+W^- cross section was approximated to NNLO using threshold resummation in (Dawson *et al.*, 2013). However, given that all diboson channels are now computed at fixed order to NNLO these calculations would have to be pushed further to compete.

For all diboson channels p_T resummation is useful, given that in these colorless final states it provides a roughly universal prediction. The prediction for the p_T spectrum of dibosons can now be tested in a new regime as was done previously for single gauge boson production. It is also important to get the correct kinematic distributions given that the dibosons are important backgrounds for many other processes including Higgs boson production. The current state of the art is NNLO+NNLL which for W^+W^- and ZZ is computed in (Grazzini *et al.*, 2015c). Given that the $W^\pm Z$ final state was only recently computed at NNLO, the current state of the art for this channel is NLO+NNLL as in (Wang *et al.*, 2013), but this should change in the near future.

For the W^+W^- channel, experimentally a jet-veto is used to control the background coming from top quark pair production, and more generally an exclusive measurement is made in different jet-multiplicities. In this

case jet-veto resummation is also needed since there is a large separation of scales between the jet-veto scale and the invariant mass of the diboson system. In fact by not including this effect, it led to early measurements of the W^+W^- cross section being significantly overestimated. The effect of the jet-veto is also correlated with p_T resummation and its impact on extrapolating to the total cross section was first pointed out for p_T resummation in (Meade *et al.*, 2014) and for jet-veto resummation in (Jaiswal and Okui, 2014). These results naively disagreed, but when taking into account scale choices and a uniform approach they agreed at NLO+NNLL (Jaiswal *et al.*, 2016). Currently the state of the art for jet-veto resummation for this channel is NNLO+NNLL as performed in (Dawson *et al.*, 2016). This slightly reduces the effect of the jet-veto on the total cross section compared to NLO+NNLL. Additionally one must include the NLO effects of $gg \rightarrow VV$ in the calculation, as was done in (Caola *et al.*, 2016) and shown to be large, but this needs to be resummed as well. Hopefully a more complete theoretical picture for this channel will be developed in the next few years and the same level of scrutiny will be applied to all diboson channels simultaneously.

2. Vector Boson Scattering and Vector Boson Fusion

From the experimental point of view, the separation between VBF and VBS comes down to whether a single gauge boson is produced from two ($VV \rightarrow V$), or whether two gauge bosons come out ($VV \rightarrow VV$). They are of course related as shown in the example VBS diagrams shown in Figure 3, as the VBF fusion process can also contribute to VBS. However, experimentally VBF where only one gauge boson is produced can be separately tagged from VBS allowing the TGC and QGC vertices to be tested separately in principle. The current theoretical state of the art is NLO in QCD corrections, and this is implemented in the MC generator **VBFNLO**. Additionally, the NLO EW corrections are also known for these processes (Andersen *et al.*, 2016). It will be important to combine all effects at this order in the future.

3. Multi-boson Production

The process $pp \rightarrow VV'V''$ is interesting for a variety of reasons at the LHC. Leptonic V decays represent some of the most relevant multi-lepton backgrounds to new physics. Additionally, they represent a new and independent avenue for testing TGCs and QGCs compared to diboson production, and as such offer consistency conditions that must be satisfied once these processes are observed with sufficient statistics. The process $W^\pm\gamma\gamma$ was calculated at leading order in (Baur *et al.*, 1997), and can be used as a test of the QGC. These were calculated at

NLO in QCD (Lazopoulos *et al.*, 2007) and again as with VBF and VBS, using the generator **VBFNLO**, the triboson process is available at NLO in QCD. The effects of EW corrections have also been calculated at NLO accuracy for instance in (Yong-Bai *et al.*, 2016) for WWW and in (Yong-Bai *et al.*, 2015) for WZZ .

B. BSM interplay

As discussed earlier, the study of multiple gauge boson production is a very important avenue for searching for new physics at the LHC due to its connection to non-Abelian physics and EWSB. In particular, before the EW sector was tested at high precision by LEP or evidence of the Higgs mechanism as the mechanism for EWSB was directly found, there were many large deviations possible. However, we are now firmly in an era where the EW structure $SU(2) \times U(1)_Y$ of the SM is firmly established, and we know the mass of the Higgs boson and its couplings to a precision that it looks very much like the SM Higgs. This in turn has led to a modernization of our theoretical and experimental understanding of how to use multi-gauge boson production to probe new physics.

For instance, the parametrization of aTGCs given in (1), manifestly breaks the gauge-invariance that we know to be true and as such it was reformulated in a “gauge-invariant” manner to fully incorporate LEP results (see (Gounaris *et al.*, 1996) for a review). This reduced the general parametrization of (1) down to a subset of related couplings, and also better formulated the search for aTGCs as deviations from the SM where $g_1^Z = g_1^\gamma = \kappa_Z = \kappa_\gamma = 1$ (appropriately rescaled by the coupling constants g of $SU(2)$ and g' of $U(1)_Y$) while all other terms are non-existent at tree-level. This is why in the later experimental sections the C and P conserving aTGCs when compared to previous experiments are given for example by $\Delta g_1^Z \equiv (g_1^Z - 1)$, $\Delta \kappa_Z \equiv \kappa_Z - 1$ and λ_Z . However, to make (1) gauge-invariant manifestly requires the introduction of new fields that transform under $SU(2) \times U(1)$ which requires a model *dependent* choice.

For several decades, up until the discovery of the Higgs and for a short time thereafter, there were many competing models for EWSB. The reason for this proliferation of models is that the Higgs mechanism in the SM has EWSB put in by hand and can not explain why the symmetry is broken. Additionally the Higgs mechanism on its own suffers from extreme fine-tuning a priori without new physics occurring beneath the TeV scale. Models such as Technicolor (Susskind, 1979; Weinberg, 1976) where EWSB occurs dynamically, and similar to other examples of spontaneous symmetry breaking that we’ve seen in nature, offered an attractive alternative. In the extreme case of strongly coupled EWSB, such as Technicolor or for instance in future reincarnations as Higgsless models (Csaki *et al.*, 2004a,b), there is no Higgs field

and the extra-modes required for gauge-invariance come from the “pions” of a larger broken symmetry. There are also models of strongly coupled EWSB which include a mode that resembles the SM Higgs, but the Higgs is also a goldstone of a larger symmetry, for instance in composite Higgs (Georgi and Kaplan, 1984) or little Higgs models (Arkani-Hamed *et al.*, 2002, 2001). In both of these cases, gauge invariance is typically parametrized through a non-linear representation of the modes, similar to one used for Chiral Lagrangians that describe the breaking of global symmetries in QCD. In weakly coupled models with fundamental scalar fields, e.g. the MSSM, there is a Higgs field that can be used directly to make gauge invariant contributions to aTGCs, and is often described in the literature as a linear representation. Regardless of what the choice of “new physics” parametrization (e.g. simply the Higgs itself) that restores gauge-invariance for aTGCs, to account for deviations such as those parametrized in (1) requires the introduction of new physics beyond the SM. However, the parametrization does have implications for the size of deviations expected and the interpretation of experimental results. Once the Higgs was discovered (and there were many hints for this from prior EW precision tests that this would be true), a linear representation is highly favored and makes any other starting point almost as contrived as assuming $SU(2) \times U(1)$ is not a good symmetry. This of course does not preclude the fact that the Higgs could be a composite from dynamical symmetry breaking, but it does restrict the form of corrections as we will see.

A useful way to look for the effects of new physics that incorporates all the previous ideas in a “model-independent” framework is to use an EFT description of the SM. This is in fact what *all* QFTs are in our modern understanding of Wilsonian renormalization. In practice for experiments what this means is to define a scale of new physics higher than the energy scale being probed at the LHC, Λ and using the fields of *the SM* to write higher dimension operators in addition to the dimension $\Delta \leq 4$ operators of the SM

$$\mathcal{L}_{EFT} = \mathcal{L}_{SM} + \sum_i \frac{\mathcal{O}_i}{\Lambda^{\Delta_i-4}}. \quad (3)$$

Given that Λ is much higher than all the scales involved, the contributions to observables are well described by a perturbative series in momenta/energy $(E/\Lambda)^{\Delta_i-4}$ provided that dimensionless couplings are $\mathcal{O}(1)$. This series then allows experiments to search for the effects of the lowest dimension operators which contribute the most to observables. In particular, at a given dimension Δ there are always a finite number of operators that can contribute to any observable. In fact through $\Delta = 6$ all operators are known and have been reduced from a general set (Buchmuller and Wyler, 1986) to a irreducible basis (Grzadkowski *et al.*, 2010). Given that there is only

one gauge invariant operator at dimension 5, the SM neutrino mass operator, all the first effects of new physics describable by an EFT occur at $\Delta = 6$ unless they are forbidden by an additional symmetry assumption. Given that the EFT includes within it all the symmetries of the SM, this serves as the best starting point for describing small deviations to the SM from physics occurring at higher mass scales. We will describe these EFT methods in more detail in Section II.B.1, their relation to previous aTGC studies and where they should and should *not* be used. It is important to note though that an EFT manifestly does *not* describe physics at a scale Λ accessible to the LHC. Given that one of the most important reasons for studying multiple EW gauge boson production is its strong coupling to the EWSB sector, the possibility that there may be new physics at the EW scale which affects these measurements is a logical possibility. In fact in almost any model of new physics that explains EWSB naturally, there are always new particles near the EW scale with EW quantum numbers that would contaminate the same final states used for the measurements of cross sections. The EFT formalism can not be used for this possibility, and currently there is almost no experimental effort in this direction. In Section II.B.2 we discuss some possible uses of multi-gauge bosons to search for new physics and test the SM in ways other than what is utilized by aTGC, aQGC and vector boson scattering measurements.

1. EFT interpretation of SM measurements

Given our current experimental and theoretical understanding, treating the SM as an EFT is an incredibly well motivated starting point. It incorporates all the symmetries and fields we know and by definition matches the current data in the limit $\Lambda \rightarrow \infty$ since we have no current evidence of BSM physics. As mentioned earlier, this is not a truly model independent description of all new physics, but it is a useful description for a subset of models which are well described through an EFT. Given a model that is well described through an EFT one can then perform a matching calculation of Wilson coefficients in the full model and EFT to set bounds on all such applicable models. In particular this formalism can describe both “linear” representations for BSM and non-linear representations that are still viable because the compositeness scale is large. For example in the Strongly Interacting Light Higgs (SILH) (Giudice *et al.*, 2007) if the scale of composite resonances m_* is well above the scale we have currently probed, the standard non-linear representation can be expanded and matched onto the EFT description used. For a detailed description of the dimension six and eight operators used in this review as well as the relations between different generator implementations and conversions with respect to anomalous

couplings, we refer the reader to (Degrande *et al.*, 2013b).

Despite EFTs being a well motivated framework that can apply to many different models, there are also drawbacks depending on how it is used experimentally and theoretically. The drawbacks come from two different fundamental reasons, however they both are related the range of validity of the EFT formalism.

The power of EFTs to describe new physics in a model independent manner comes explicitly from the expansion $(E/\Lambda)^{\Delta_i-4} \ll 1$. However, this intrinsically means that the effects on SM observables are also tiny. If one introduces an operator into an effective Lagrangian and naively calculates the experimental limits, the most discriminating power comes from the opposite regime $(E/\Lambda)^{\Delta_i-4} \sim 1$ where the EFT is not valid and an infinite set of operators would be needed to describe the physics. Beyond invalidating the nature of the EFT expansion, calculating naively with a given operator with a contribution $(E/\Lambda)^{\Delta_i-4}$ to a matrix element will also given an apparent unitarity violation at some energy. This is different from the motivations of tree-level unitarity violation in vector boson scattering studies when the nature of EWSB was unknown. Unitarity violation from an EFT operator is *completely unphysical* and again simply reflects using an EFT incorrectly. This point is theoretically well understood, however, both ATLAS and CMS still refer to unitarization methods when they use an EFT framework for multi-gauge boson measurements (mainly due to these inconsistent limits $(E/\Lambda)^{\Delta_i-4} \ll 1$ and $(E/\Lambda)^{\Delta_i-4} \sim 1$). Of course experiments are free to “parametrize” new physics however they want, but it *defeats the model-independent purpose* of using an EFT description. Once a unitarization method is chosen there is an explicit model dependence introduced.

The other drawback to using EFTs is again related to using EFTs in an invalid region, and comes from the careful application of matching Wilson coefficients to underlying theories. Naively LEP, LHC or other experiments can set bounds on the dimensionful Wilson coefficients $c_i g_i/\Lambda^{\Delta_i-4}$, and these can be compared between experiments. In fact this is often done to show the increased sensitivity of the LHC, including in this review, and to compare to other experiments. However, it is important to keep in mind that the dimensionful Wilson coefficient, c , always arises from some matching calculation where new physics at a scale M is integrated out. For example G_F is the Wilson coefficient of the four-fermion operator that arises from integrating out the massive W and Z . In a general case there can be a coupling g for a new state to the SM and a mass M of the new state, which if integrated out at tree-level to form a $\Delta = 6$ operator gives a Wilson coefficient

$$c \sim \frac{g^2}{M^2}. \quad (4)$$

While naively one could use this EFT up to energy scales

$c^{-1/2}$, if $g < 1$ one would reach the scale of the mass of the new physics M much earlier, thereby invalidating the EFT description of this model if this energy scale were probed. Alternatively though, if $g > 1$ this implies the true mass scale $M > c^{-1/2}$. This clearly illustrates why an underlying understanding of how power counting the couplings of new physics and matching to Wilson coefficients can vastly affect whether a “bound” on an EFT operator has any meaning or in what class of theories it has relevance. In particular in weakly coupled theories, the range of validity can be much reduced, and by definition the underlying effects should be small. Furthermore, it is quite possible that new physics doesn’t have SM EFT operators generated at tree-level 4, and the Wilson coefficients arise at leading order from loop-effects which then even more so invalidate the conclusions. In strongly coupled theories, these factors can be overcome naively, but of course at strong coupling there isn’t theoretical control. Therefore using experimental bounds on EFT operators to match to these strongly coupled theories and constrain them is an empty statement unless augmented by an additional non-generic argument that provides theoretical control. In addition, now that a Higgs boson has been discovered, we know that there can’t be parametrically large shift in the physics of EWSB implying that new physics must appear weakly coupled at the scales we are probing at the LHC. Therefore we *must* be careful about the power counting of Wilson coefficients when comparing experimental results, otherwise we are led to false conclusions as we will now illustrate.

If one takes the bounds set by different experiments on the same SM EFT operators, naively one can conclude that one experiment has increased sensitivity over another. For instance in the recent theoretical analysis of (Butter *et al.*, 2016) it was concluded that diboson measurements at the LHC set better bounds than LEP on operators that contribute to aTGCs. However, as we will show in an example pointed out in (Contino, 2016), this is not actually the case when one considers how this theory is matched to an underlying model. The comparison between these two experiments is straightforward because there are three operators at $\Delta = 6$ that contribute to aTGC measurements

$$\begin{aligned} \mathcal{O}_{HW} &= D_\mu h^\dagger W^{\mu\nu} D_\nu h \\ \mathcal{O}_{HB} &= D_\mu h^\dagger B^{\mu\nu} D_\nu h \\ \mathcal{O}_{3W} &= \text{Tr} (W_{\mu\nu} W^{\nu\rho} W_\rho^\mu). \end{aligned} \quad (5)$$

In (Butter *et al.*, 2016) a fit was performed demonstrating the increased sensitivity that the LHC had from Run 1 compared to LEP, an example being shown in Figure 4. However, this increased sensitivity as described in (Butter *et al.*, 2016) comes from the high p_T regions available at the LHC. Therefore, one must be careful whether or not the operators used in Equation 5 correspond to theories in which the EFT description is valid and the

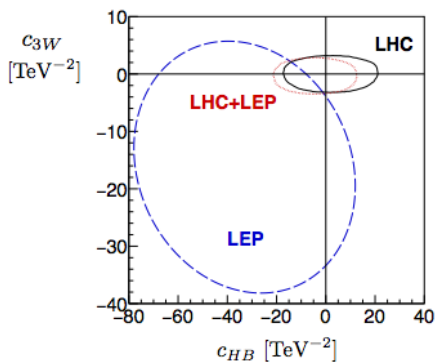


FIG. 4 Figure from (Butter *et al.*, 2016) demonstrating increased sensitivity of LHC over LEP.

increased sensitivity is not an artifact of the high p_T tail of the EFT. For example, one potentially viable model with alternative EWSB is the SILH model. In this model there are two parameters which describe the new physics, a coupling g_* and a mass scale m_* . As with any model, a matching calculation to a SM EFT can be performed, leading to specific predictions for the Wilson coefficients. In this case there are different power countings of couplings and masses for the different operators of Equation 5, and when the bounds on the operators are recast in terms of the m_* and g_* one reaches a contradiction. For the case of $c_{HW,HB}$ this leads to the following relation

$$c_{HW,HB} \sim \frac{g}{m_*^2} \left(\frac{g_*^2}{16\pi^2} \right) \rightarrow m_* \gtrsim 300 \text{ GeV} \left(\frac{g_*}{4\pi} \right) \quad (6)$$

where at strong coupling the mass scale needs to be $m_* \gtrsim 300 \text{ GeV}$, but the LHC has already probed this territory. In the case of c_{3W} , where as in Figure 4, we naively see huge gains compared to LEP, in reality the SILH power counting gives

$$c_{3W} \sim \frac{g}{m_*^2} \left(\frac{g^2}{16\pi^2} \right) \rightarrow m_* \gtrsim 20 \text{ GeV} \quad (7)$$

which shows that this is a completely invalid assumption to bound this type of new physics through EFTs. Now this example of course doesn't invalidate the use of EFTs at the LHC. However, it illustrates the limitations in an EFT operator analysis, i.e. there could be large swaths of motivated models that can not be described/tested consistently in an EFT framework.

EFTs have been pursued by experimentalists for their inherent genericity, but using them to compare to different experimental data has to be done with caution and theory prejudices in mind. For instance, if one takes the correct LEP bounds on dimension-six operators, they are quite constrained, and there may not be increased sensitivity at the LHC yet, unless the high p_T behavior is exploited. As a way around this, ATLAS and CMS moved forward with a program that looked at the effects

on aQGCs by ignoring all dimension-six operators and only including dimension-eight operators in their analysis. This defeats the original motivation for using EFTs, as it is focusing solely on extremely non-generic models where dimension-six Wilson coefficients vanish or are highly suppressed and the new physics generates leading dimension-eight operators. While not impossible (Liu *et al.*, 2016), it is not model-independent whatsoever and requires very specific mechanisms to override a standard power counting. Using the dimension-six operators may not show improvement compared to LEP for aQGCs for instance yet, but nevertheless the bounds will apply to a much larger set of models.

EFTs are a robust theoretical tool, and a welcome introduction to the experimentalists arsenal forcing gauge invariance and the inclusion of a Higgs-like particle when organizing search strategies for multi-boson physics. However, as we've reviewed there are many potential drawbacks as well, and they are not a panacea for model dependent statements in experimental measurements. It simply is a fact that at this point the LHC in many channels is not better suited to bounding models where an EFT description is applicable. However, this does not mean that the LHC doesn't have enormous capabilities for searching for new physics and constraining a wide variety of models that LEP could never constrain. In the next section we put forward a recommendation for how this could be done more generically and that applies to both EFT based models and those not describable by one at the LHC.

2. Fiducial Cross Sections and BSM recommendations

As discussed in II.B.1, EFTs provide useful ways to search for new physics, but they also have inherent disadvantages at hadron colliders. On top of the drawbacks associated with EFTs, they are completely useless for describing physics at scales directly accessible to the LHC. However, multi-boson processes still are one of, if not the most important channels to search for new physics due to their connection to EWSB. In principle, new physics accessible at LHC energies would be discovered or constrained by direct searches in groups other than the SM groups in ATLAS or CMS. However, inherent in many scenarios of BSM physics there are difficult kinematic regions to access which direct searches in other groups have trouble accessing. In this section we demonstrate examples where SM measurements can provide powerful discriminating power for BSM physics even when the EFT description is invalid. Most importantly the measurements we propose are also equally powerful for searching for BSM physics described by EFTs and avoid all the issues EFT searches have associated with unitarization, strong coupling, power counting, and spurious symmetry arguments.

Before discussing generalities it is useful to look at an interesting example from Run 1, that came about not from a theoretical effort originally, but from a series of measurements by ATLAS and CMS. The W^+W^- cross section as measured by ATLAS and CMS systematically was always higher than the predicted NLO cross section at both 7 and 8 TeV. This eventually led to theoretical developments already covered involving higher fixed order calculations as well as higher order resummed calculations. However, an intriguing possibility was that this could have also been caused by a new BSM contribution to the W^+W^- cross section measurement. An example of this was provided in (Curtin *et al.*, 2013a) where in SUSY the pair production of Charginos would lead to a final state $pp \rightarrow \chi^+\chi^- \rightarrow W^+W^-\chi^0\chi^0$. In the detector this gives the same final state of l^+l^- +missing transverse energy (MET) as used for the cross section. Typically such a scenario is searched for in direct SUSY searches, but if the spectrum is such that the kinematics is similar to that of the SM background it is very difficult to disentangle and could be mistaken. That the kinematics is similar to multiboson final states naturally arises if EW BSM states are similar to the EW scale. However, this also arises if the mass splittings between the states that are responsible for production and what they decay into are similar to the EW scale. In (Curtin *et al.*, 2013b) it was realized that using the W^+W^- cross section measurement itself could be used to bound a number of these scenarios. In particular, by using this measurement the first bounds on RH sleptons that exceeded LEP limits were found. This has been applied to other SM channels as well, for instance the $t\bar{t}$ final state in (Czakon *et al.*, 2014).

Having BSM physics which mimics SM final states is a very generic phenomenon. For example many different types of models were written to attempt to explain the W^+W^- cross section excess (Curtin *et al.*, 2013a,b, 2014; Jaiswal *et al.*, 2013; Rolbiecki and Sakurai, 2013). Some of these did not even rely directly on partners of EW gauge bosons for production, but nevertheless led to final states that potentially contaminated the SM measurement. In general, almost all Exotic/SUSY searches have gaps when a SM background becomes kinematically similar to it. Dedicated search strategies can be setup to try to close these gaps, but it is very model dependent and takes a lot of effort to understand the SM background. Naturally, as demonstrated in (Curtin *et al.*, 2013b), a SM measurement is already an incredibly powerful place to search for this type of generic BSM physics. However, this has only been carried out by theorists and the methods could be pushed further by those making the measurements. Unfortunately, as discussed so far, multi-gauge boson measurements are only used by the experiments to search for EFTs, aTGC and aQGCs, none of which are relevant for the processes described here. Fortunately, there is a way out already adopted

by BSM groups within ATLAS and CMS, and recently it has started to be adopted by the SM groups and should be extended to all channels.

We recommend that for all multi-gauge boson measurements, the experiments place bounds via upper limits on fiducial cross sections as an alternative to EFT interpretations. ATLAS began doing this originally in the SUSY group, by in addition to interpreting their signal regions through models, they included 95% CL upper limits on signal regions (Aad *et al.*, 2012l) independent of interpretation. ATLAS and CMS have given fiducial cross sections in multi-gauge boson production measurements, and in a few cases 95% CL upper limits on signal regions as well, which we strongly endorse. By giving upper limits on cross sections in different fiducial regions, any model can be interpreted whether or not an EFT approach is valid or a model must be used. There is no loss in discriminating power compared to previous studies of SM cross sections. For instance signal regions used for aTGCs or aQGCs based on high p_T or invariant mass can be kept, and theorists can easily recast the bounds. However, it avoids the interpretation issues for the experiments on the validity of EFTs, aTGCs, aQGCs. In particular, the theoretical statement of when a certain model or approach is theoretically valid resides with the theorists. Additionally, it allows for the direct comparison with models clearly not describable by current theoretical approaches implemented by the experimental groups, for instance the W^+W^- example given earlier. Furthermore, by reducing the time spent on theoretical interpretation, more “signal” regions, could be investigated. Importantly, this does not have to be motivated solely from the BSM perspective. Having more differential distributions in fiducial regions that are well understood by the experiments and released to the theoretical community can point to where more SM theoretical effort is needed e.g. NNLO QCD, NLO EW, or various resummations.

III. EXPERIMENTAL SETUP

Detailed descriptions of the Large Hadron Collider, the ATLAS and the CMS detectors are available elsewhere (Aad *et al.*, 2008; Chatrchyan *et al.*, 2008; Evans and Bryant, 2008). The definitions of the physics objects used in the described analyses vary in both efficiency and purity, and are selected based on the needs of the specific physics process under study. CMS makes extensive use of particle flow algorithms which use all the CMS subsystems (Beaudette, 2013; Chatrchyan *et al.*, 2011a).

The triggers selecting the final states of interest to be recorded for offline analysis are generally based on the selection of energetic electrons or muons if present in the final state, with thresholds depending on the data taking period under study and its instantaneous luminosity. The trigger thresholds for electrons and muons are efficient

for W and Z boson leptonic decays, and reconstruction thresholds also maintain high efficiency. In the absence of charged leptons in the signature, other characteristics such as the presence of energetic photons or large missing transverse energy (MET) are utilized. The hadronic decay products of W or Z bosons are not required to satisfy a trigger. The performance of the ATLAS trigger system is described in more detail elsewhere (Aad *et al.*, 2012k, 2015e; ATLAS Collaboration, 2012b), and a detailed description of the CMS system is given in (Adam *et al.*, 2006; Chatrchyan *et al.*, 2010; Khachatryan *et al.*, 2016f).

The performance of ATLAS and CMS for photons (Aaboud *et al.*, 2016b; Aad *et al.*, 2014a; ATLAS Collaboration, 2011, 2012a; Khachatryan *et al.*, 2015g), electrons (Aad *et al.*, 2014b; ATLAS Collaboration, 2014a; Khachatryan *et al.*, 2015f), muons (Aad *et al.*, 2014e,f; Chatrchyan *et al.*, 2013h), MET (Aad *et al.*, 2012j, 2016h; ATLAS Collaboration, 2013, 2014b; Khachatryan *et al.*, 2015h), and jets (Aad *et al.*, 2013a,b, 2015c; ATLAS Collaboration, 2015; Chatrchyan *et al.*, 2011a; Khachatryan *et al.*, 2016b; Lampl *et al.*, 2008) is well-documented.

The sensitivity to anomalous gauge couplings is greatest at high mass, when the hadronic decay products of the gauge bosons are merged into a single unresolved jet. Nevertheless, the mass of such jets is cleanly measured (Aad *et al.*, 2016d; Khachatryan *et al.*, 2014b) and they are key tools for such studies. In Figure 5 the jet mass for a sample of lepton plus MET plus jets with top pair enhancements illustrates the cleanliness of the merged hadronic W boson decays.

For the gauge bosons, the studies of photons are already listed above. For W bosons, the leptonic decays are studied using the lepton (electron or muon) plus MET signature. Hadronic decays are captured as a mass peak in the resolved dijet case at low transverse momentum and in the boosted monojet case at high transverse momentum. For Z bosons dilepton pairs are used, both electrons and muons (Aad *et al.*, 2012a; Chatrchyan *et al.*, 2014b); τ leptons are not included with one exception detailed in Section IV.H. In addition, the larger branching fraction neutrino pair decay mode is tagged using a MET signature. Hadronic Z boson decays are not fully resolved in the (di)jet mass from W boson decays.

The results described in this review combine the boson signatures at 7 and 8 TeV center of mass energy in a variety of final states detailed in Sections IV to VII. Limits on anomalies in the gauge couplings appear in Sections VIII and IX, derived by exploring the high mass spectrum of the (multi-)bosons themselves or by use of the transverse momentum of one of the bosons or one of the boson decay products depending on the specific analysis. Background processes are evaluated by using Monte Carlo models, by extrapolating from background dominated control regions or by data-driven methods,

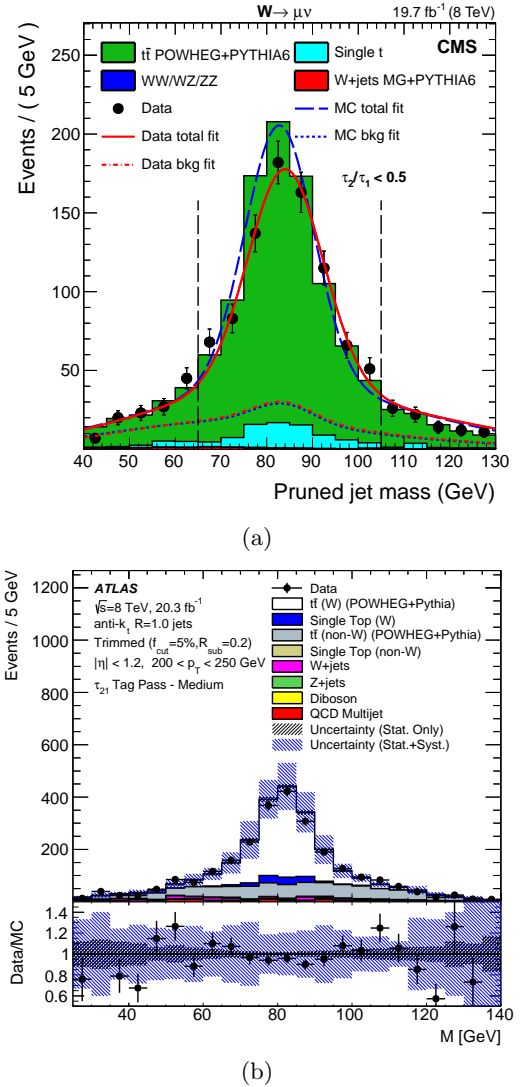


FIG. 5 Jet mass distributions in events with a leptonic W boson decay and jets with cuts appropriate for boosted top jets: (a) CMS (Khachatryan *et al.*, 2014a) for the muon channel and (b) ATLAS (Aad *et al.*, 2016d) for the combined electron and muon channels.

depending on the importance of the background source and reliability of the available MC modeling.

IV. DIBOSON PRODUCTION

A. $\gamma\gamma$ Production

Measurement of diphoton production represents a stringent test of higher order perturbative QCD corrections, since beyond the LO quark-antiquark annihilation the quark-gluon channel contributes at NLO and the gluon-gluon channel box diagram at NNLO. This process is also sensitive to soft fragmentation contributions where photons arise from the fragmentation of colored partons.

With the discovery of a Higgs boson (Aad *et al.*, 2012i; Chatrchyan *et al.*, 2012b) a resonant production mode has become available to which diphoton production constitutes an irreducible background that needs to be well-characterized for detailed Higgs boson studies as well as for searches for new resonances.

Both ATLAS (Aad *et al.*, 2012b, 2013c) and CMS (Chatrchyan *et al.*, 2012a, 2014a) have studied diphoton production at 7 TeV in data samples with integrated luminosities of up to 5 fb^{-1} . The measured total cross sections are clearly most compatible with the theoretical predictions at NNLO, and partial N^3LO results including the NLO corrections to the gluon-gluon channel box diagram lead to a further 7% increase of the total cross section prediction (Campbell *et al.*, 2016).

Both experiments provide in addition differential cross section measurements as a function of, for example, the invariant mass, transverse momentum and azimuthal separation of the diphoton system. As illustrated in Figure 6, these measurements show better agreement with respect to NNLO predictions compared to NLO ones. Mass scales slightly below 1 TeV are probed already with these 7 TeV data sets.

B. $W\gamma$ Production

Studies of the $W\gamma$ final state have been published by ATLAS (Aad *et al.*, 2011b, 2012g, 2013f) and CMS (Chatrchyan *et al.*, 2011c, 2014c) at 7 TeV using data samples with integrated luminosities of up to 5 fb^{-1} , where the W boson was observed in the leptonic final state with the charged lepton being either an electron or a muon and the photon was required to be isolated. Both experiments provide inclusive diboson cross sections, and ATLAS additionally provides exclusive cross sections where central jet activity has been vetoed. As illustrated in Figure 7, CMS finds the cross section to be compatible with the MCFM prediction at NLO in QCD as a function of the photon E_T out to 100 GeV, while ATLAS measures inclusive cross sections higher than the NLO prediction in the inclusive process for high- E_T photons. NNLO corrections are found to increase the NLO prediction by $\approx 20\%$, hence improving the agreement with the measured cross sections (Grazzini *et al.*, 2015a).

The SM TGC of $WW\gamma$ contributes to $W\gamma$ production. Limits on the anomalous triple gauge couplings (aTGC) $\Delta\kappa_\gamma$ and λ_γ are set by comparing their effect on the photon E_T spectrum with the observed spectrum as shown in Figure 8. ATLAS uses exclusive events to set limits on anomalous couplings in order to increase the expected sensitivity in high E_T photon events, which otherwise also tend to exhibit more jet activity in the SM.

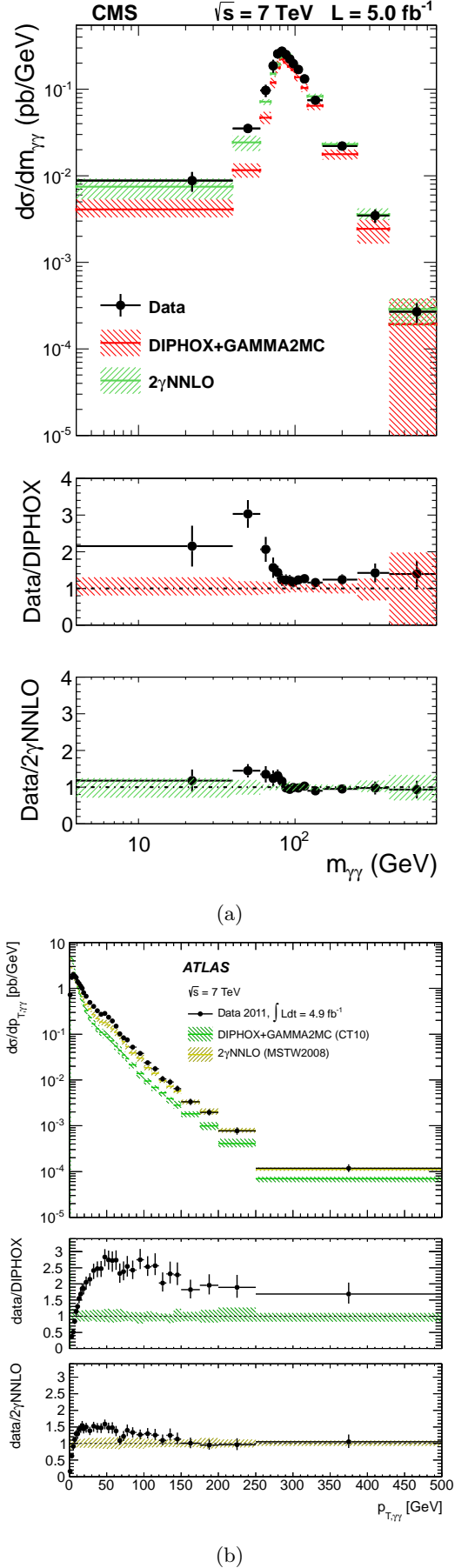


FIG. 6 Comparison of $\gamma\gamma$ differential cross section measurements as a function of (a) the invariant mass (Chatrchyan *et al.*, 2014a) and (b) transverse momentum (Aad *et al.*, 2013c) of the diphoton system with NLO and NNLO predictions.

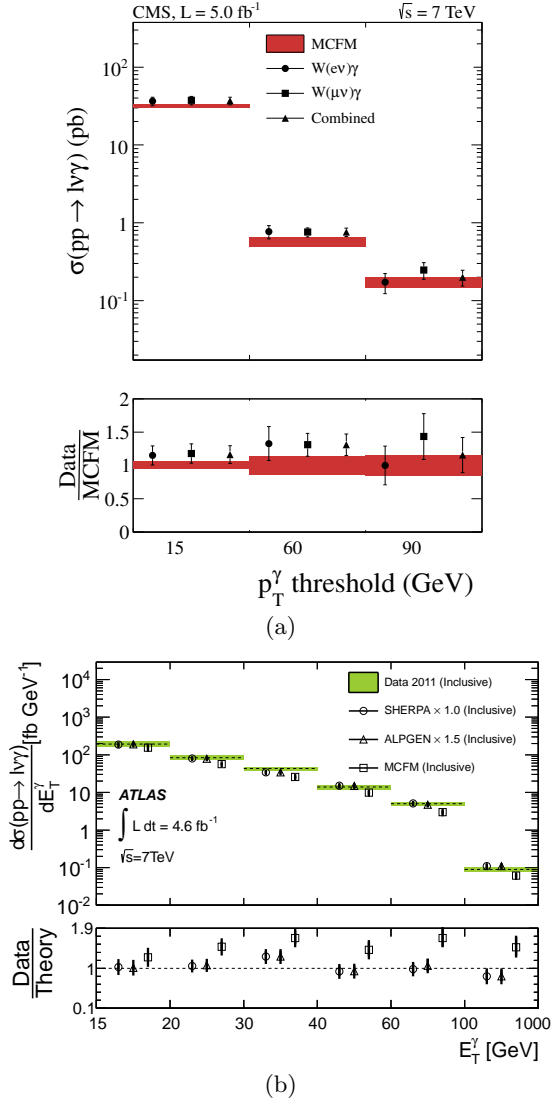


FIG. 7 7 TeV $W\gamma$ inclusive cross section as a function of photon E_T : (a) comparison of the CMS measurements with MCFM predictions (Chatrchyan *et al.*, 2014c) and (b) comparison of the ATLAS measurements with MCFM, Sherpa and ALPGEN (Mangano *et al.*, 2003) predictions, where the latter two have been scaled to match the total number of observed events in data (Aad *et al.*, 2013f).

C. $Z\gamma$ Production

The production of $Z\gamma$ pairs in final states with an oppositely charged electron or muon pair and an isolated photon has been studied by ATLAS (Aad *et al.*, 2011b, 2012g, 2013f) and CMS (Chatrchyan *et al.*, 2011c, 2014c) at 7 TeV using data samples with integrated luminosities of up to 5 fb^{-1} . Both experiments provide inclusive diboson cross sections, and ATLAS additionally provides exclusive cross sections where central jet activity has been vetoed. As illustrated in Figure 9, both ATLAS and CMS find the cross section to be compatible with the MCFM prediction at NLO in QCD as a function of the

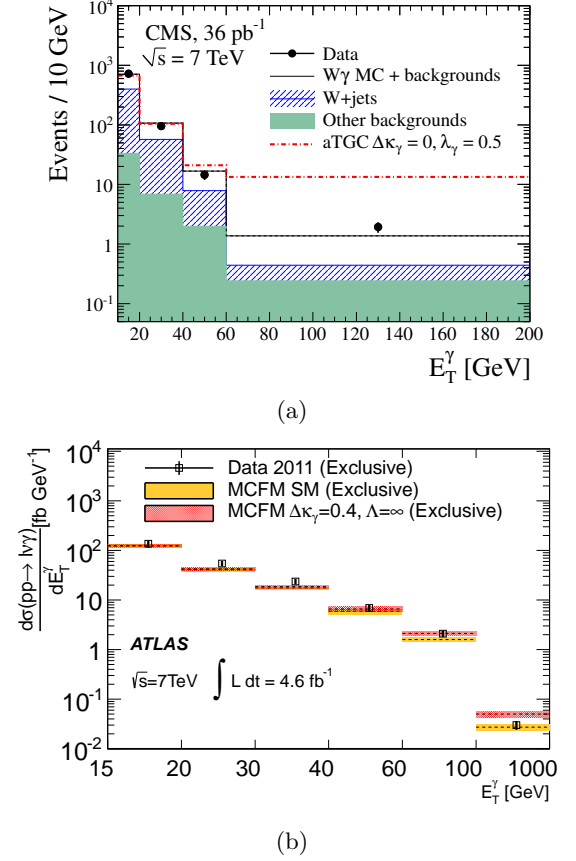


FIG. 8 Effect of aTGCs in the $W\gamma$ final state at 7 TeV: (a) photon E_T spectrum measured by CMS with an inclusive selection (Chatrchyan *et al.*, 2011c) and (b) $W\gamma$ cross section measured by ATLAS as a function of photon E_T with an exclusive selection vetoing central jets (Aad *et al.*, 2013f).

photon E_T . NNLO corrections are found to be much smaller compared to $W\gamma$ and increase the NLO prediction by $\approx 8\%$ (Grazzini *et al.*, 2015a). The same final state has been studied by ATLAS (Aad *et al.*, 2016g) and CMS (Khachatryan *et al.*, 2015d) in 8 TeV data samples with integrated luminosities of up to 20 fb^{-1} . Both inclusive and exclusive production cross sections are extracted and found to be in agreement with MCFM and NNLO predictions. Figure 10 shows the inclusive differential cross section measurements as a function of photon E_T from both experiments.

SM $Z\gamma$ production arises from photons radiated from initial state quarks or radiative Z boson decays to charged leptons as well as fragmentation of final state quarks and gluons into photons. $Z\gamma Z$ and $Z\gamma\gamma$ anomalous triple gauge couplings h_3^V, h_4^V ($V = Z, \gamma$) are constrained by comparing their effect on the photon E_T spectrum with the observed spectrum. The sensitivity to these aTGCs can be significantly enhanced by studying the $Z \rightarrow \nu\bar{\nu}$ decay mode due to the six times larger branching fraction compared to the charged lepton decay

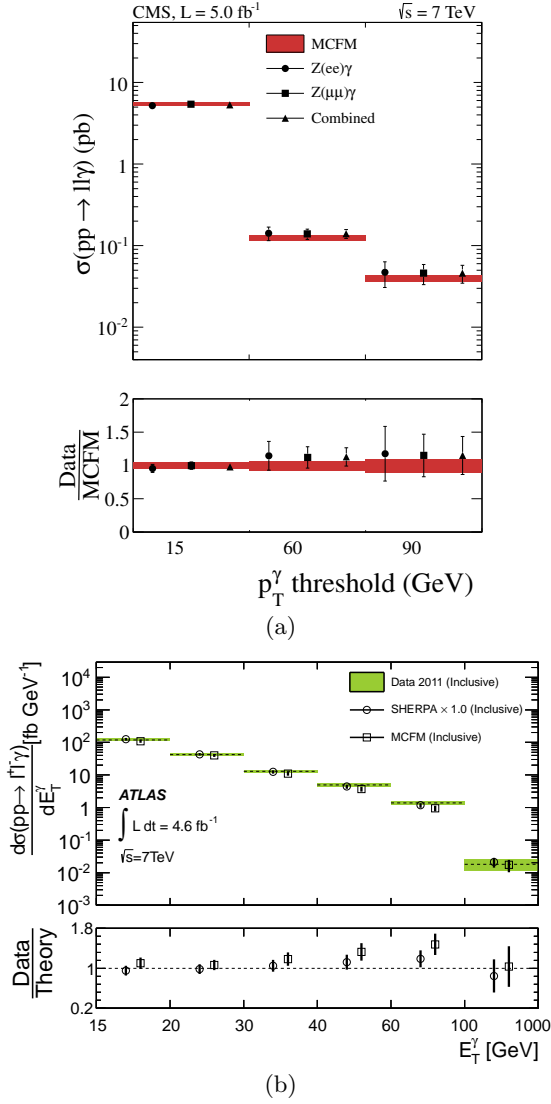


FIG. 9 7 TeV $Z\gamma$ inclusive cross section as a function of photon E_T : (a) comparison of the CMS measurements with MCFM predictions (Chatrchyan *et al.*, 2014c) and (b) comparison of the ATLAS measurements with MCFM and Sherpa predictions, where the latter has been scaled to match the total number of observed events in data (Aad *et al.*, 2013f).

modes and the increased detector acceptance. Both ATLAS (Aad *et al.*, 2013f, 2016g) and CMS (Chatrchyan *et al.*, 2013b; Khachatryan *et al.*, 2016d) have studied the resulting final state of large missing transverse energy and an energetic isolated photon in the 7 and 8 TeV data sets and observe production rates in agreement with theoretical predictions. The photon E_T spectra extend to about 1 TeV and are utilized to constrain aTGC contributions as illustrated in Figure 11, which also serves to set the scale for the sensitivity of the data to non-SM couplings. Again, ATLAS uses exclusive events to set limits on anomalous couplings in order to increase the expected sensitivity in high E_T photon events, which

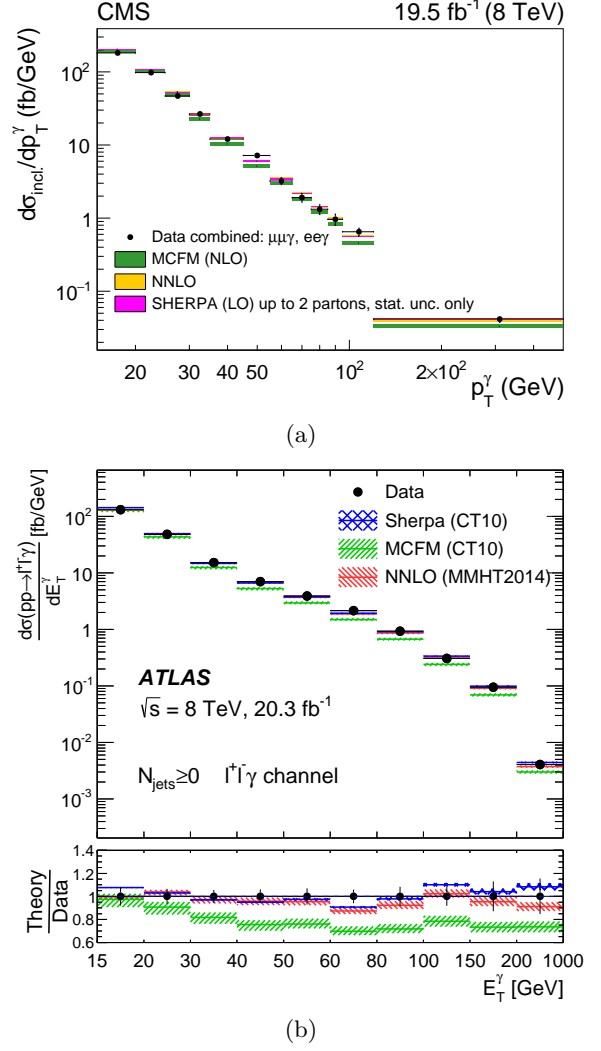


FIG. 10 8 TeV $Z\gamma$ inclusive cross section as a function of photon E_T in comparison with MCFM, Sherpa and NNLO predictions: (a) CMS (Khachatryan *et al.*, 2015d), where Sherpa is normalized to the NNLO cross section and (b) ATLAS (Aad *et al.*, 2016g).

otherwise also tend to exhibit more jet activity in the SM.

D. W^+W^- Production

For the case of W^+W^- production, two decay modes have been studied. In the leptonic mode, both W bosons decay into a charged lepton and a neutrino (MET). In the semi-leptonic case, one W boson decays leptonically while the other decays hadronically. The leptonic mode has less background but the branching fraction of the W pair is about six times smaller than in the semi-leptonic case when considering the decay modes involving electrons and muons. In addition, the WW pair mass in a semi-leptonic decay can be fully reconstructed up to

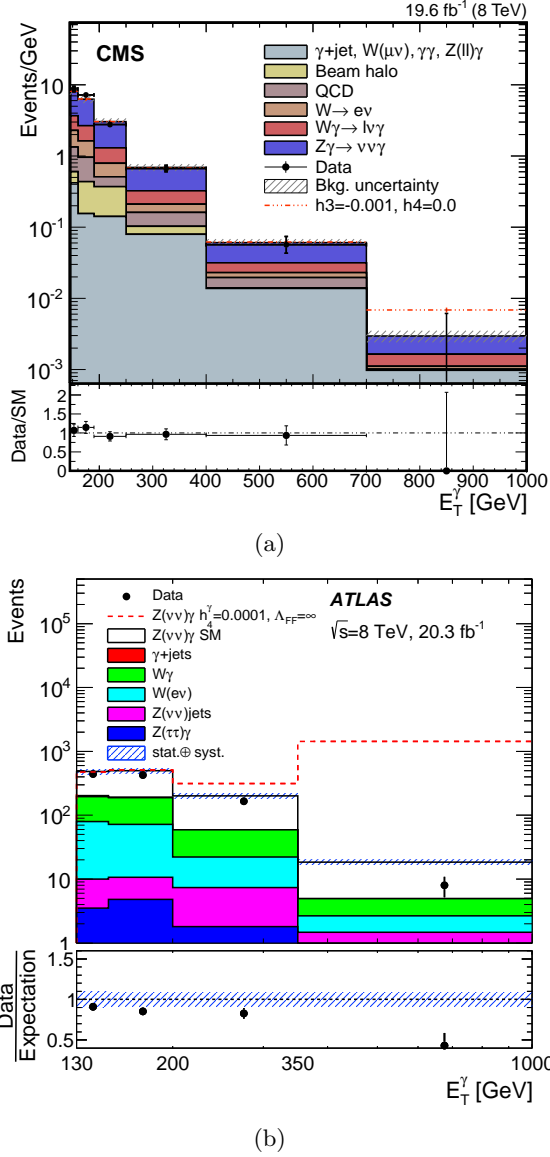


FIG. 11 Photon E_T spectrum at 8 TeV for the $Z\gamma \rightarrow \nu\bar{\nu}\gamma$ final state and effect of a representative aTGC on the spectrum for (a) CMS (Khachatryan *et al.*, 2016d) and (b) ATLAS (Aad *et al.*, 2016g) with an exclusive selection vetoing central jets.

a quadratic ambiguity, so that the energy at the TGC vertex is directly measurable in contrast to the leptonic decay case. However, in the semileptonic decay mode hadronic W boson decays cannot be fully distinguished from hadronic Z boson decays due to limited dijet mass resolution. The semileptonic WW decay is hence studied together with the semileptonic WZ decay in Section IV.E. Both the $WW\gamma$ and the WWZ SM TGC contribute to WW production in distinction to $W\gamma$ production. Deviations from the SM TGC are labeled by parameters λ_V , $\Delta\kappa_V$ ($V = Z, \gamma$) following the nomenclature already introduced for $W\gamma$ production, and Δg_1^Z .

The production of WW pairs in the fully leptonic

decay mode with an oppositely charged lepton (electron or muon) pair and missing transverse energy in the final state has been studied by ATLAS (Aad *et al.*, 2011a, 2012d, 2013d) and CMS (Chatrchyan *et al.*, 2011b, 2013d) at 7 TeV using data samples with integrated luminosities of up to 5 fb^{-1} . Figure 12 shows the spectra of the highest p_T lepton of the final state pair as observed by ATLAS and CMS. Also shown are the modifications to the spectrum caused by aTGCs for which no evidence was found. Both experiments do not include resonant produc-

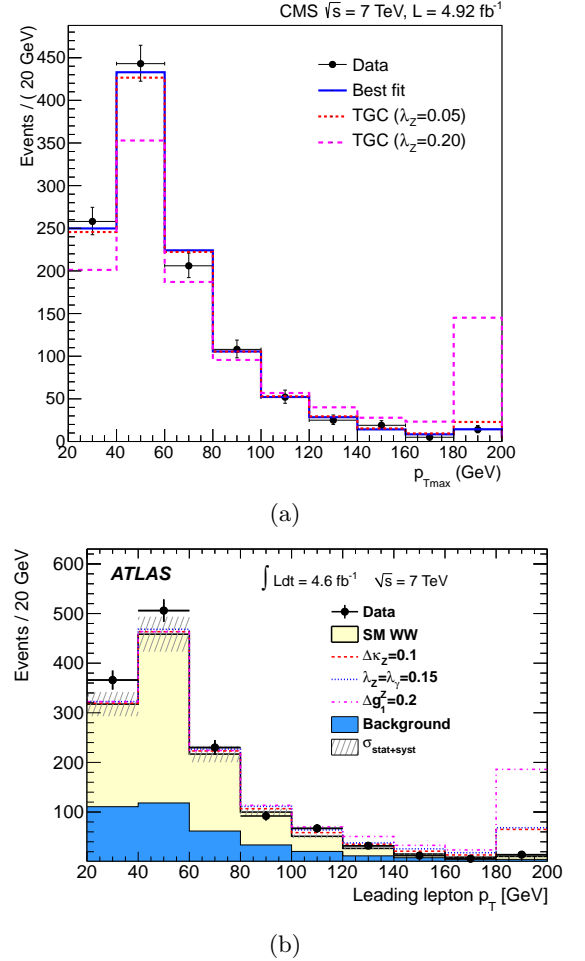


FIG. 12 Leading lepton p_T spectra in 7 TeV fully leptonic WW candidate events and the impact of different anomalous TGC predictions for (a) CMS (Chatrchyan *et al.*, 2013d) and (b) ATLAS (Aad *et al.*, 2013d). The last bin includes the overflow.

tion via the Higgs boson in their signal model and observe WW production cross sections larger than (then state-of-the-art) NLO predictions, consistent with the significant cross section enhancements predicted by NNLO calculations (Gehrmann *et al.*, 2014). Additional measurements such as the ratio of the inclusive WW cross section to the Z boson cross section (Chatrchyan *et al.*, 2013d) and normalized fiducial cross section as function of the lead-

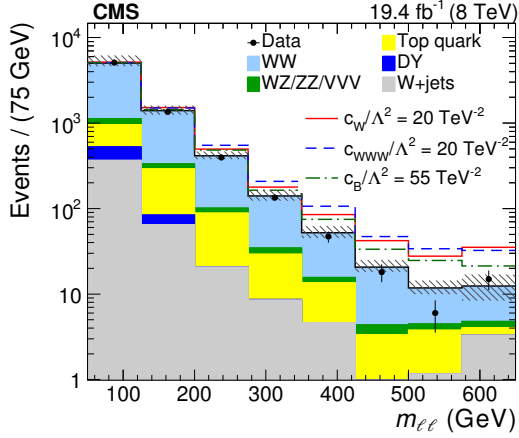


FIG. 13 Dilepton mass spectrum in 8 TeV fully leptonic WW candidate events and impact of different anomalous TGC predictions (Khachatryan *et al.*, 2015c). The last bin includes the overflow.

ing lepton p_T (Aad *et al.*, 2013d) are provided as well and are found to be in agreement with theory predictions.

WW production in the fully leptonic decay mode has been studied by ATLAS (Aad *et al.*, 2016e) and CMS (Chatrchyan *et al.*, 2013f; Khachatryan *et al.*, 2015c) as well in 8 TeV data samples with integrated luminosities of up to 20 fb^{-1} . While ATLAS includes Higgs-mediated WW production as signal, CMS subtracts the small corresponding expected contribution. The measured fiducial and total production cross sections are found to be consistent with NNLO predictions (Grazzini *et al.*, 2016a), and (normalized) differential cross sections are measured as a function of kinematic event variables. CMS includes a measurement of the total WW production cross section in events with exactly one jet, while ATLAS vetoes events with reconstructed jets. No evidence for anomalous $WW\gamma$ and WWZ TGCs is observed and hence limits on the corresponding parameters are set. An alternative EFT formulation of aTGC with dimension six operators is introduced (DeGrande *et al.*, 2013c) with corresponding coefficients c_W , c_{WWW} and c_B that can be mapped to the LEP formulation which allows comparisons with earlier data. Figure 13 shows the dilepton mass spectrum as measured by CMS (Khachatryan *et al.*, 2015c) together with the distorted spectral shape that would result from aTGC contributions. Figure 14 gives an overview of the total WW production cross sections measured at hadron colliders at different center of mass energies in comparison with the expectations of theory.

ATLAS has studied WWj production in the $e\mu$, MET and exactly one jet final state (Aaboud *et al.*, 2016f) in the full 8 TeV data set, where the largest background from top quark production is suppressed with a b -jet veto. Both $WW + 1$ jet and $WW + \leq 1$ jets (the latter in combination with the 0-jet analysis (Aad *et al.*,

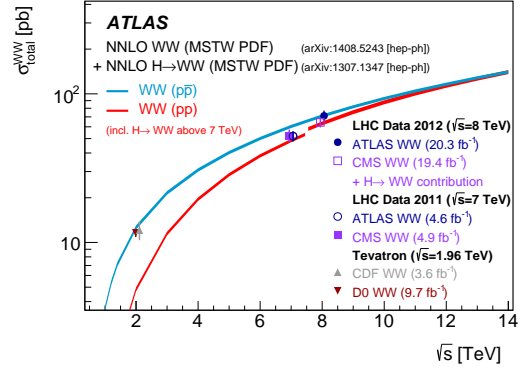


FIG. 14 Comparison of measured total WW production cross sections at hadron colliders and NNLO theory predictions as a function of \sqrt{s} (Aad *et al.*, 2016e).

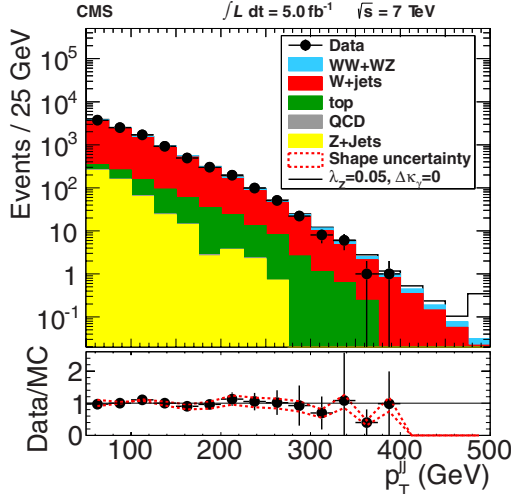
2016e)) fiducial cross sections are provided and in good agreement with state-of-the-art theoretical predictions. Extrapolating the $WW + \leq 1$ jets fiducial measurement to the total cross section, better agreement with the theoretical prediction is observed than in the 0-jet analysis, and the overall uncertainty improves by 12%. The ratio of $WW + 1$ jet to $WW + 0$ jets fiducial cross sections is found to be consistent with theoretical predictions.

E. $W^\pm V$ Production

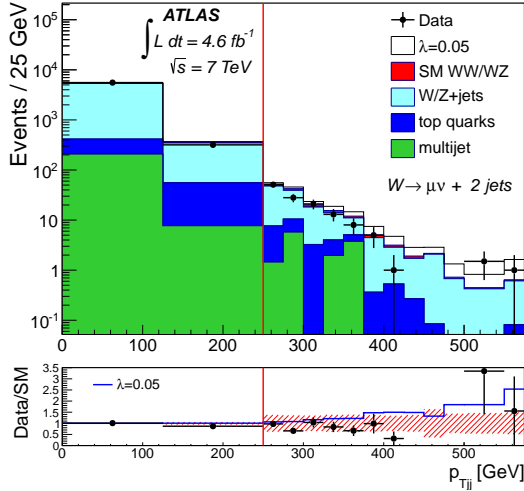
Semileptonic WV decays ($V = W, Z$) with one charged lepton (electron or muon), missing transverse energy and exactly two jets in the final state have been studied by ATLAS (Aad *et al.*, 2015d) and CMS (Chatrchyan *et al.*, 2013c) at 7 TeV using data samples with integrated luminosities of up to 5 fb^{-1} . The background (dominated by W +jets production) is much more important in this case compared to the leptonic decay modes and care is needed to assess the level of background accurately. The measured sums of the inclusive WW and WZ cross sections are found to be in good agreement with the NLO SM prediction. Both experiments constrain anomalous WWZ and $WW\gamma$ couplings utilizing the p_T distribution of the hadronically decaying V in a narrow mass window $75 \text{ GeV} < m_{jj} < 95 \text{ GeV}$ that improves the signal-to-background ratio and enhances the expected contribution of WW over WZ . Figure 15 shows the observed dijet- p_T spectra measured by both experiments in the muon channel together with the potential impact of aTGCs.

F. ZV Production

CMS has studied semileptonic ZV decays ($V = W, Z$), where the Z boson decays into a pair of b -tagged jets in 18.9 fb^{-1} pp data at 8 TeV (Chatrchyan *et al.*, 2014d). The second V boson is detected through leptonic final



(a)



(b)

FIG. 15 Dijet- p_T spectra in the muon channel of 7 TeV semileptonic WV candidate events and the impact of different anomalous TGC predictions for (a) CMS (Chatrchyan *et al.*, 2013c) and (b) ATLAS (Aad *et al.*, 2015d). The last bin includes the overflow.

states giving rise to MET (mainly due to $Z \rightarrow \nu\bar{\nu}$), one charged lepton (electron or muon) and MET ($W \rightarrow \ell\nu$), or a same-flavor, oppositely-charged lepton pair (electrons or muons, $Z \rightarrow \ell\bar{\ell}$). A significant $ZV \rightarrow b\bar{b}V$ signal is observed, and the simultaneously measured WZ and ZZ cross sections are found to be in agreement with their NLO predictions, as illustrated in Figure 16. The fiducial cross sections for high p_T (V) events are as well found to be in good agreement with NLO theory predictions and hence give no indication of anomalous TGC contributions.

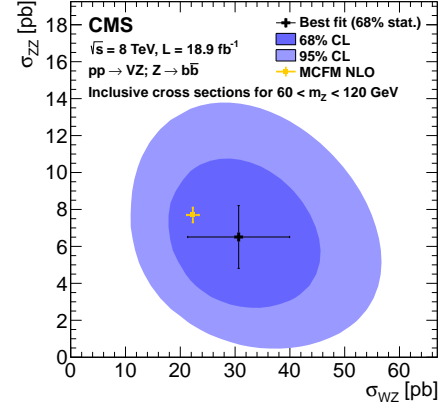


FIG. 16 68% and 95% CL cross section contours for WZ and ZZ production as observed in $ZV \rightarrow b\bar{b}V$ events (Chatrchyan *et al.*, 2014d) in comparison with NLO theory predictions.

G. $W^\pm Z$ Production

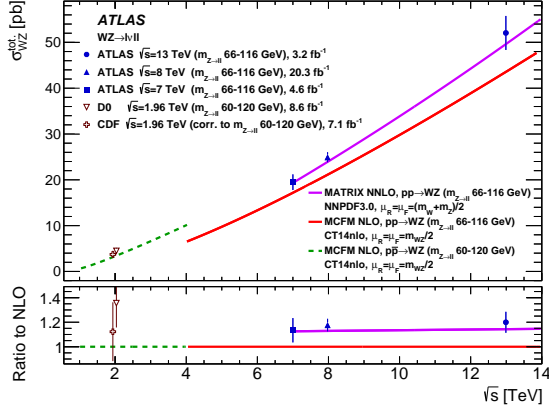
The production of $W^\pm Z$ boson pairs in the three lepton plus MET final state where the Z boson decays into an electron or muon pair while the W boson decays leptonically has been studied by ATLAS (Aad *et al.*, 2012e,h, 2016f) and CMS (Khachatryan *et al.*, 2016e) at both 7 TeV and 8 TeV using data samples with integrated luminosities of up to 5 fb^{-1} and 20 fb^{-1} , respectively.

The selected data sets are quite cleanly dominated by the signal process. The measured WZ cross sections are found to be consistent with NLO SM predictions, and differential cross sections for a variety of kinematic variables such as the transverse momentum of the Z and W boson (Aad *et al.*, 2016f) or leading jet p_T and jet multiplicity (Khachatryan *et al.*, 2016e) are provided. The cross section ratios of inclusive W^+Z and W^-Z production are measured as well by ATLAS and found to be in agreement with NLO theory predictions. A first calculation of the SM cross section at NNLO (Grazzini *et al.*, 2016b) that became available only after above ATLAS analyses were published, significantly improves the agreement between prediction and measurements as illustrated in Figure 17.

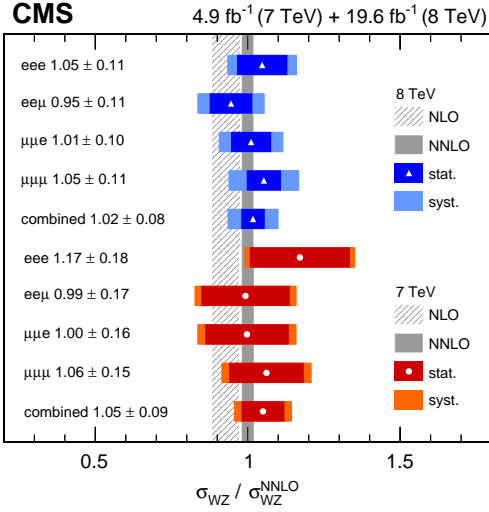
WZ production only includes the TGC of WWZ as opposed to WW production which has both WWZ and $WW\gamma$ SM vertices. The variables chosen to search for aTGC are the p_T of the Z boson and the transverse mass of the $W^\pm Z$ system, shown in Figure 18. As the observed spectra agree with the SM prediction, stringent limits on aTGC contributions are derived.

H. ZZ Production

Pairs of Z bosons cannot be created at a single vertex in the SM because there is no SM TGC available; only



(a)

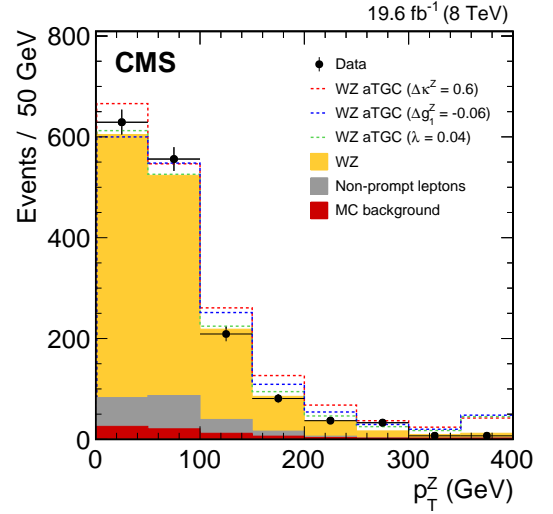


(b)

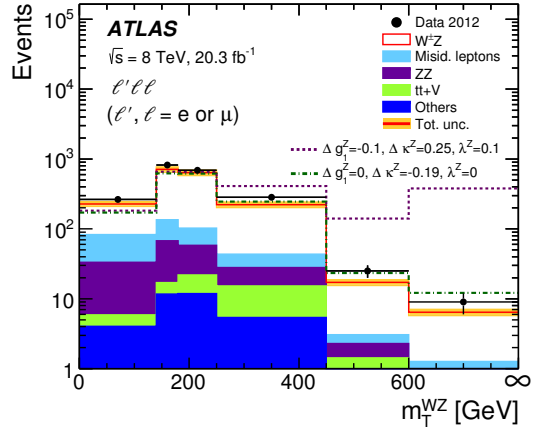
FIG. 17 Comparison of $W^\pm Z$ production cross section measurements with NLO and NNLO predictions (a) at various center of mass energies (Aaboud *et al.*, 2016c) and (b) in the individual and combined channels at 7 TeV and 8 TeV (Khachatryan *et al.*, 2016e).

WWZ and $WW\gamma$ exist in the SM. The HZZ vertex is here not considered to be a TGC vertex. Anomalous $ZZ\gamma$ and ZZZ couplings can be added with an effective Lagrangian approach and parametrized using two CP-violating (f_4^V) and two CP-conserving (f_5^V) parameters ($V = \gamma, Z$) in direct analogy to the $Z\gamma$ case, where there is also no SM TGC.

The production of ZZ boson pairs has been studied in two decay modes. In the “ 4ℓ ” mode, both Z bosons decay into same-flavor, oppositely-charged lepton pairs, resulting in a very low-background, kinematically fully reconstructable final state that however suffers from low statistics due to the branching fractions involved. In the “ $2\ell 2\nu$ ” mode, one Z boson decays into a same-flavor, oppositely-charged lepton pair, while the other one de-



(a)



(b)

FIG. 18 Observed (a) p_T distribution of the Z boson (Khachatryan *et al.*, 2016e) and (b) transverse mass spectrum of the $W^\pm Z$ system (Aad *et al.*, 2016f) in $W^\pm Z$ candidate events at 8 TeV and the impact of different anomalous TGC predictions.

cays to neutrinos, giving rise to large missing transverse energy in the final state. While this decay mode suffers from larger background contributions and is not kinematically fully reconstructable, it benefits from better signal statistics due to the increased branching fraction and detector acceptance.

Both ZZ decay modes have been studied by ATLAS (4ℓ : (Aaboud *et al.*, 2016d; Aad *et al.*, 2012c,f, 2013e), $2\ell 2\nu$: (Aaboud *et al.*, 2016d; Aad *et al.*, 2013e)) and CMS (4ℓ : (Chatrchyan *et al.*, 2013e; Khachatryan *et al.*, 2015b), $2\ell 2\nu$: (Khachatryan *et al.*, 2015e)) at both 7 TeV and 8 TeV using data samples with integrated luminosities of up to 5 fb $^{-1}$ and 20 fb $^{-1}$, respectively. CMS includes the decay of one Z boson into τ leptons in the 4ℓ

decay mode. The measured ZZ cross sections are found to be consistent with NLO SM predictions, as illustrated in Figures 19–21. NNLO corrections (Grazzini *et al.*, 2015b) increase the expected fiducial cross sections by about 15% with respect to NLO predictions.

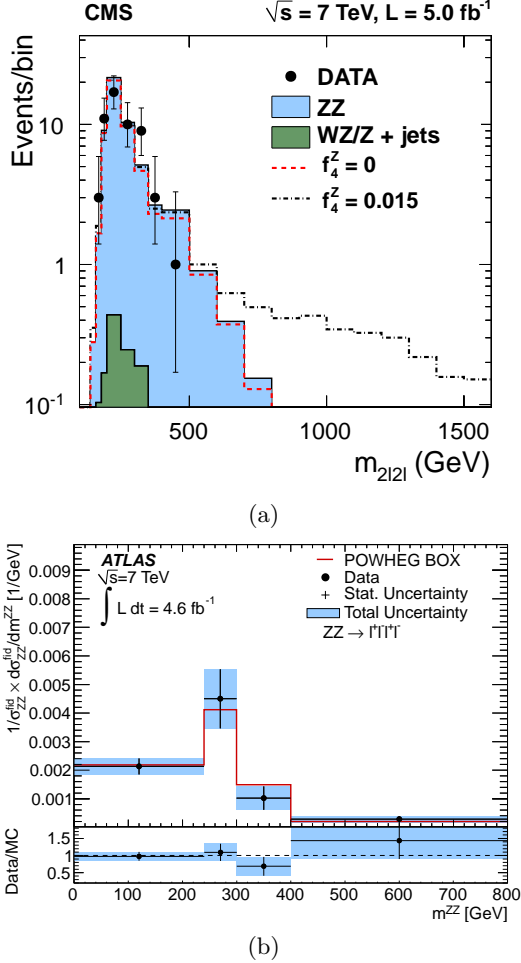


FIG. 19 (a) ZZ mass spectrum in the 4ℓ decay channel ($\ell = e, \mu$) and the impact of anomalous TGCs (Chatrchyan *et al.*, 2013e). (b) Unfolded ZZ fiducial cross sections in the 4ℓ decay channel in bins of ZZ mass (Aad *et al.*, 2013e).

Figures 19 and 20 show that in the 4ℓ final state masses of the ZZ pair up to about 0.5 TeV at 7 TeV and 0.8 TeV at 8 TeV are explored in a situation where the ZZ signal dominates. The dilepton, or Z , p_T in the $2\ell 2\nu$ final state at 8 TeV extends out to about 0.5 TeV as presented in Figure 21; however here the ZZ signal has large backgrounds compared to the 4ℓ final state.

Limits on aTGCs arise when the spectra shown are confronted with models having deviations from the SM. As is customary, 95% Confidence Level (CL) limits are derived for aTGCs either as limits in one dimension, or in two dimensions allowing two couplings to vary freely from their SM values as will be shown later.

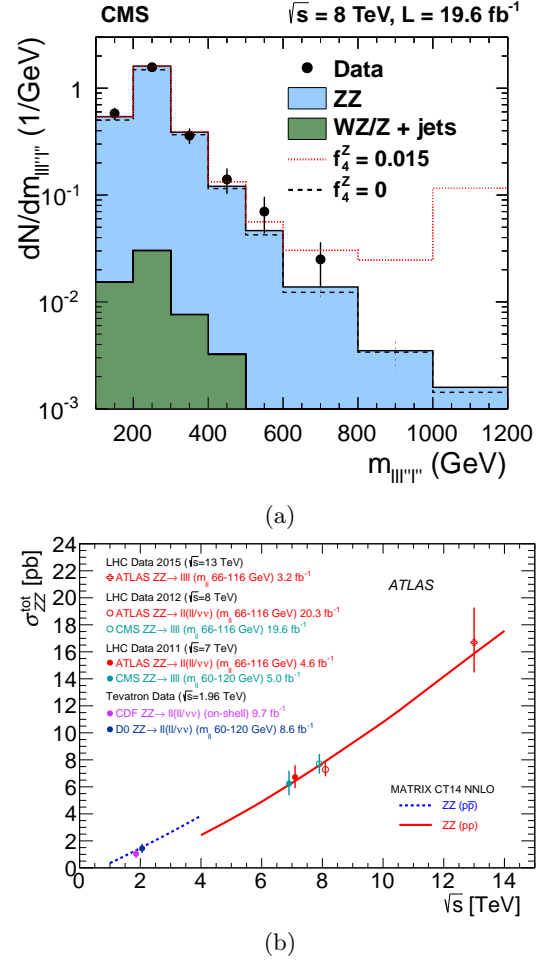


FIG. 20 (a) ZZ mass spectrum in the 4ℓ decay channel ($\ell = e, \mu$) and the impact of anomalous TGCs (Khachatryan *et al.*, 2015b). (b) Comparison of ZZ production cross sections measured at hadron colliders and NNLO predictions as a function of center of mass energy (Aaboud *et al.*, 2016d).

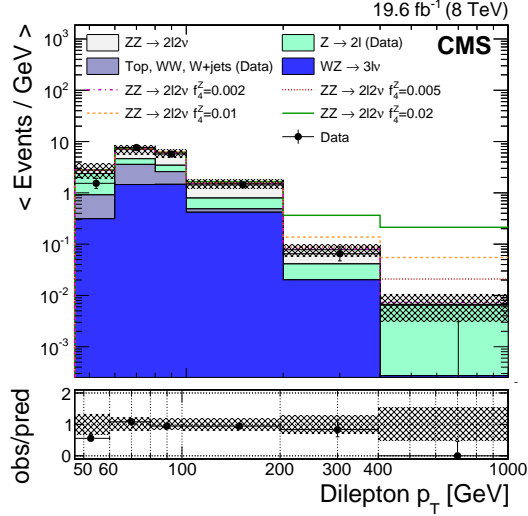
V. TRIBOSON PRODUCTION

The inclusive production of three gauge bosons has a much lower cross section compared to that for the production of two gauge bosons. Large aQGC are searched for in an EFT formulation with dimension six or eight operators. The lowest dimension operators that *only* introduce aQGC are of dimension eight.

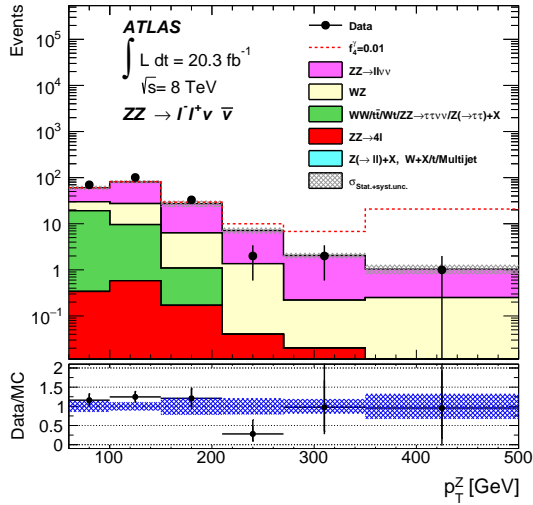
A. $W\gamma\gamma$ Production

The largest inclusive triple gauge boson cross section is that for $W\gamma\gamma$ production. The best signal to background ratio is achieved when studying the leptonic W boson decay modes into a charged lepton (e or μ) and a neutrino (MET), leading to a final state with one isolated lepton, MET and two isolated photons.

ATLAS (Aad *et al.*, 2015b) has studied this final state



(a)

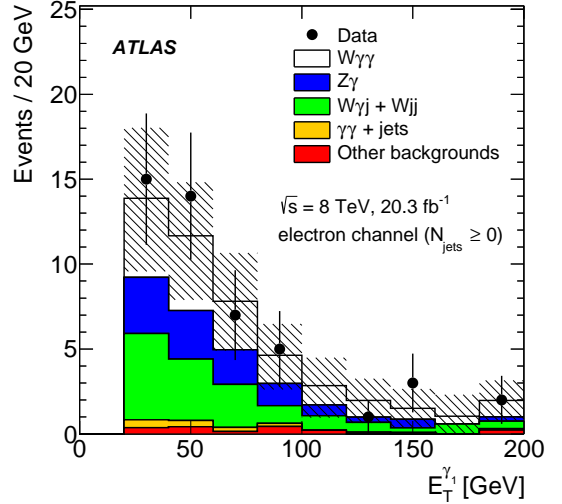


(b)

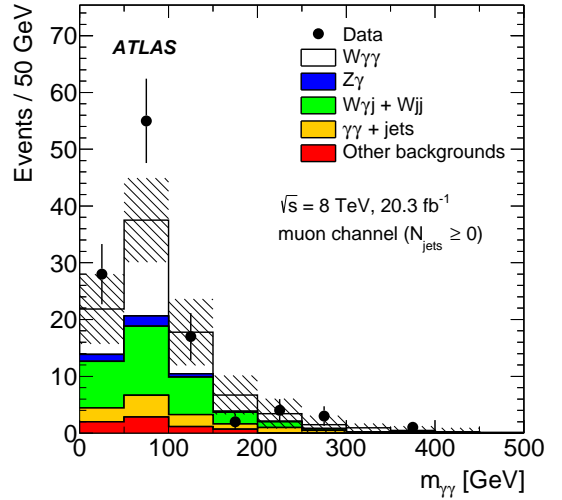
FIG. 21 Dilepton (Z) p_T distributions in ZZ candidate events at 8 TeV in the $2\ell 2\nu$ decay channel ($\ell = e, \mu$) and the impact of anomalous TGCs: (a) (Khachatryan *et al.*, 2015e) and (b) (Aaboud *et al.*, 2016d).

in an 8 TeV data sample with an integrated luminosity of 20 fb^{-1} and observes first evidence for the $W\gamma\gamma$ process at the level of $> 3\sigma$, with the production rate in agreement with theoretical NLO predictions. ATLAS additionally provides exclusive cross sections where additional jet activity has been vetoed.

Figure 22 shows leading photon E_T and diphoton invariant mass distributions in $W\gamma\gamma$ candidate events which extend out to about 0.2 TeV and 0.4 TeV, respectively. There is no evidence for a large non-SM contribution to the production process. Limits on anomalous $WW\gamma\gamma$ couplings are placed using the tail of the diphoton invariant mass distribution and vetoing additional jet activity to constrain dimension eight operators with couplings f_{T0} , f_{M2} and f_{M3} .



(a)



(b)

FIG. 22 $W\gamma\gamma$ candidate events at 8 TeV in the $\ell\nu\gamma\gamma$ final state (Aad *et al.*, 2015b): (a) E_T spectrum of the leading photon in the electron channel and (b) diphoton invariant mass distribution in the muon channel.

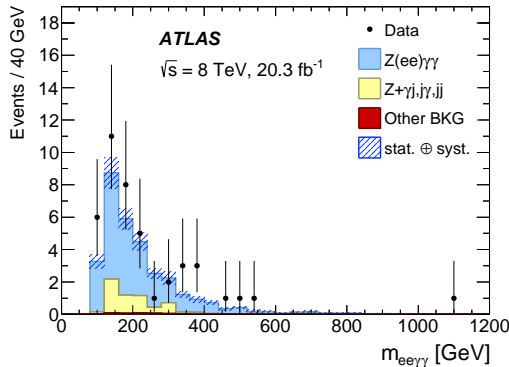
B. $Z\gamma\gamma$ Production

SM $Z\gamma\gamma$ triboson production arises from Z boson production with photons radiated off from initial state quarks or radiative Z boson decays to charged leptons as well as fragmentation of final state quarks and gluons into photons and cannot occur in a single vertex due to the lack of neutral $ZZ\gamma\gamma$ and $Z\gamma\gamma\gamma$ QGCs in the SM. Such anomalous QGCs can be introduced with EFT dimension eight operators with couplings f_{T0} , f_{T5} , f_{T9} , f_{M2} and f_{M3} .

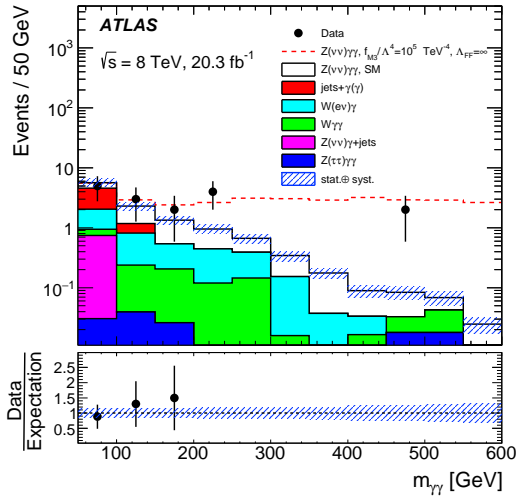
The production of $Z\gamma\gamma$ tribosons has been studied in two decay modes, each of which requires two isolated photons in the final state. In the “ 2ℓ ” mode, the Z boson decays into a same-flavor, oppositely-charged lepton (elec-

tron or muon) pair, resulting in a low-background, kinematically fully reconstructable final state. In the “ 2ν ” mode, the Z boson decays into neutrinos, giving rise to large missing transverse energy in the final state. While this decay mode suffers from larger background contributions and is not kinematically fully reconstructable, it benefits from an increased branching fraction and detector acceptance in order to constrain anomalous QGCs.

ATLAS (Aad *et al.*, 2016g) has studied the 2ℓ and 2ν decay modes in an 8 TeV data sample with an integrated luminosity of 20 fb^{-1} and provides the first cross section measurement for $Z\gamma\gamma$ production with $> 5\sigma$ significance. The observed production rate is found to be consistent with theoretical NLO predictions. ATLAS also provides exclusive cross sections where additional jet activity has been vetoed.



(a)



(b)

FIG. 23 $Z\gamma\gamma$ candidate events at 8 TeV (Aad *et al.*, 2016g). (a) Spectrum of the four-body invariant mass $m_{ee\gamma\gamma}$ in the electron channel of the $\ell\ell\gamma\gamma$ final state. (b) Diphoton invariant mass distribution in the exclusive $\nu\nu\gamma\gamma$ final state and potential impact of aQGCs.

Figure 23 shows the four-body $ee\gamma\gamma$ and diphoton invariant mass distributions in $Z\gamma\gamma$ candidate events which

extend out to about 1.1 TeV and 0.5 TeV, respectively. With no evidence found for a large non-SM contribution to the production process, ATLAS places limits on anomalous QGCs using exclusive fiducial cross sections with high diphoton invariant mass requirements in the 2ℓ and 2ν decay modes.

C. $WV\gamma$ Production

Semileptonic $WV\gamma$ decays ($V = W, Z$) with one charged lepton (electron or muon), missing transverse energy, at least two jets and an energetic photon in the final state represent an extension of the study of WV production described in Section IV.E. While the large hadronic branching fraction of the W or Z boson makes this triboson production mode more accessible, W and Z bosons cannot be fully distinguished since the dijet mass resolution is comparable to their mass difference. However, the $WW\gamma$ mode dominates because the $WZ\gamma$ cross section is smaller and the dijet mass resolution provides some discrimination. The expected SM QGC contributions to $WV\gamma$ production are $WWZ\gamma$ and $WW\gamma\gamma$.

The production of $WV\gamma$ has been searched for by CMS (Chatrchyan *et al.*, 2014e) at 8 TeV using a data sample with integrated luminosity of 19 fb^{-1} . The $W\gamma$ plus jet background dominates the signal. An upper limit on $WV\gamma$ production is placed based on the observed data yields corresponding to about 3.4 times the SM NLO QCD theoretical expectation. Nevertheless useful limits can be placed on large contributions of aQGCs using the photon p_T spectrum as shown in Figure 24. Constraints

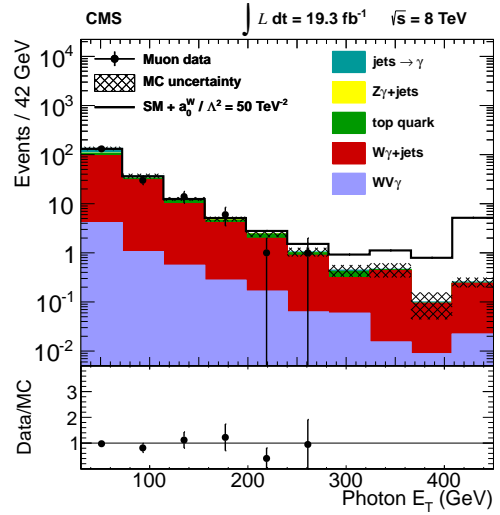


FIG. 24 Photon p_T spectrum in $WV\gamma$ candidate events in the $\ell\nu jj\gamma\gamma$ final state at 8 TeV and potential impact of aQGCs (Chatrchyan *et al.*, 2014e).

are provided on the dimension eight operator with coupling f_{T0} and alternatively on the dimension six opera-

tors with couplings a_0^W, a_C^W for $WW\gamma\gamma$ and κ_0^W, κ_C^W for $WWZ\gamma$ vertices, respectively.

D. $W^\pm W^\pm W^\mp$ Production

The production of $W^\pm W^\pm W^\mp$ constitutes the largest inclusive triple gauge boson cross section with three massive bosons and includes contributions from TGCs, Higgs production and the SM $WWWW$ QGC. The possible decay modes include the very clean fully leptonic final state $\ell^\pm \nu \ell^\pm \nu \ell^\mp \nu$ exhibiting three charged leptons (e or μ) and MET as well as a semileptonic final state $\ell^\pm \nu \ell^\pm \nu jj$ with two leptons of the same sign (e or μ), MET and two jets that – while suffering from larger background contributions – benefits from a larger branching fraction.

ATLAS has studied both of these signatures at 8 TeV using a data sample with an integrated luminosity of 20 fb^{-1} (Aaboud *et al.*, 2016h). To optimize signal sensitivity, the selection criteria are adjusted according to the number of Same Flavor Opposite Sign (SFOS) lepton pairs present in the leptonic final state, and according to the same sign lepton flavor combination in the semileptonic final state. The latter is a “spin-off” from the $W^\pm W^\pm jj$ analysis described in Section VII.B, where the dijet invariant mass and rapidity separation cuts have been modified to select W boson decays instead.

The data are described well by the signal and background model for both final states as illustrated in Figure 25 and the combined signal significance is $\approx 1\sigma$. Given the current statistical limitation to establish the signal cross section, upper limits on $W^\pm W^\pm W^\mp$ production are placed based on the observed data yields in good agreement with predictions from theory.

Possible aQGC contributions are constrained using the spectrum of the triplepton transverse mass in the $\ell^\pm \nu \ell^\pm \nu \ell^\mp \nu$ final state and the sum of scalar p_T for all selected objects (leptons, jets, MET) in the $\ell^\pm \nu \ell^\pm \nu jj$ final state, where data extend to 1 TeV. Dimension eight operators with couplings $f_{S0,1}$ are probed.

VI. VECTOR BOSON FUSION

Vector Boson Fusion (VBF, $VV \rightarrow V$) is an exclusive process wherein a constituent of each proton emits a boson which then both fuse together to form a single boson. The proton emission leads to remnant jets near to the initial beam directions. That topology is exploited in attempting to isolate the specific process. The emitted virtual vector boson can be a photon, W boson or Z boson.

Typically the rapidity difference of the forward/backward or “tag” jets is large as is the dijet mass. These facts are used to enhance the VBF process. Nevertheless, the final states are also available to other

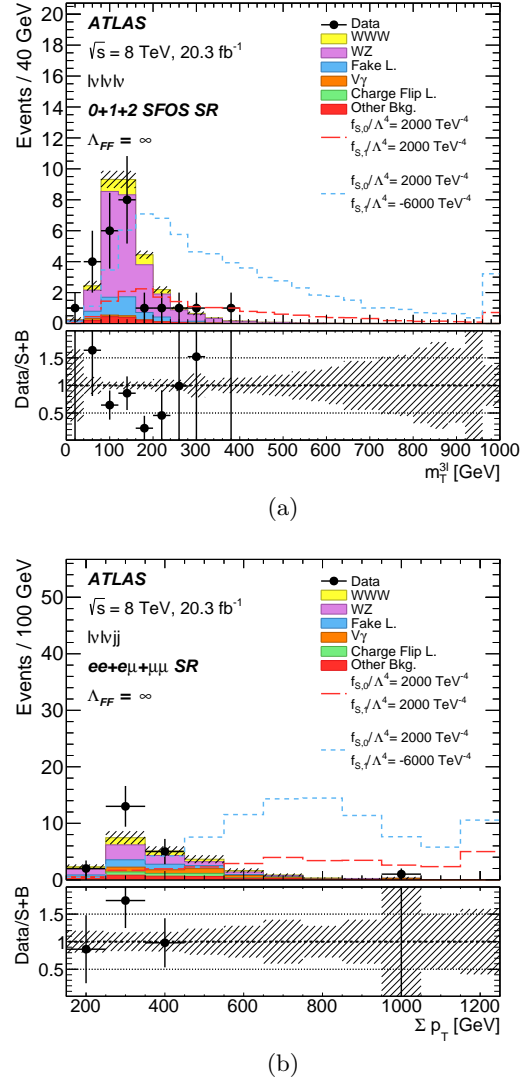


FIG. 25 $W^\pm W^\pm W^\mp$ candidate events at 8 TeV (Aaboud *et al.*, 2016h): (a) spectrum of the triplepton transverse mass in the $\ell^\pm \nu \ell^\pm \nu \ell^\mp \nu$ final state and (b) sum of scalar p_T for all selected objects (leptons, jets, MET) in the $\ell^\pm \nu \ell^\pm \nu jj$ final state. The potential impact of aQGCs is shown as well.

processes whose amplitudes interfere with the VBF process, making a completely clean separation impossible, even at a conceptual level.

The study of VBF events also constrains aTGC contributions in a way complementary to diboson production, since in the VBF process the two bosons radiated by the protons exhibit space-like four-momentum transfer and not time-like four-momentum as is the case in diboson production (Baur and Zeppenfeld, 1993). The sensitivity of such limits can be competitive with that from diboson production (Éboli and Gonzalez-Garcia, 2004).

A. Wjj Production

The largest cross section VBF process studied at the LHC is the production of a W boson in association with two jets. The leptonic decay of the W boson is used in the examination of the lepton (e, μ) plus MET plus two jet final state.

CMS has studied this signature at 8 TeV using a data sample with integrated luminosity of 19 fb^{-1} (Khachatryan *et al.*, 2016c). As seen in Figure 26 (a), the EW

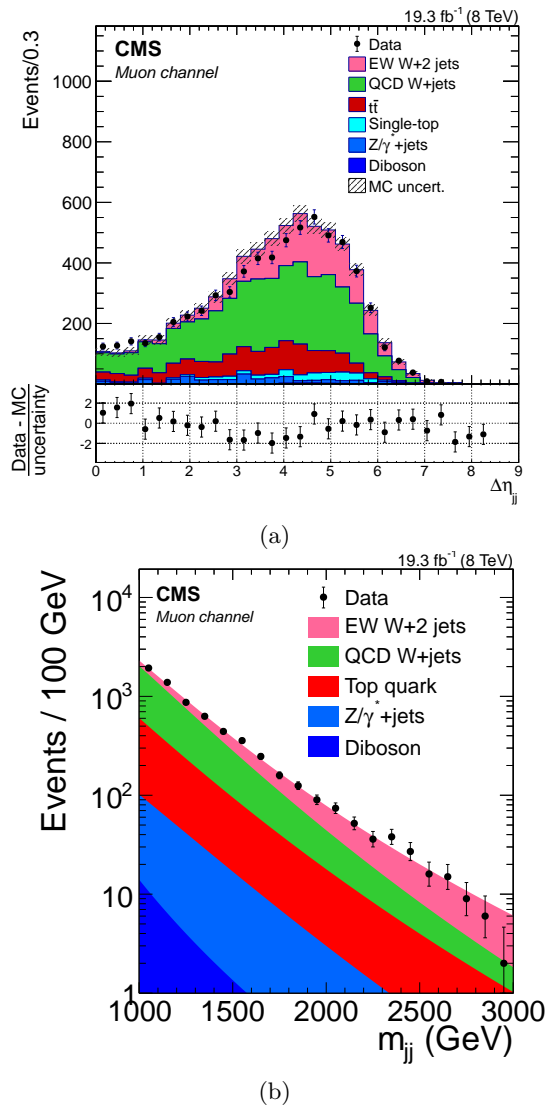


FIG. 26 VBF- W candidate events in the $lvjj$ final state at 8 TeV (Khachatryan *et al.*, 2016c). (a) Pseudorapidity difference of the "tag" jets. (b) Dijet mass spectrum of the "tag" jets.

processes can be large in carefully selected regions of phase space. Normalizing the dominant background arising from W boson plus jets production via the strong interaction with a Boosted Decision Tree technique, the dijet mass tail above 1 TeV is examined as shown in Fig-

ure 26 (b). At large masses, greater than about 2 TeV, the EW processes dominate the data sample. The largest background, QCD W plus jets production, falls with mass more rapidly than the EW signal. The fiducial electroweak production cross section of a W boson in association with two jets is extracted and found to be consistent with the SM prediction.

The SM $WW\gamma$ and WWZ TGCs contribute to this process, but the aTGC limits are presently not competitive with the limits coming from inclusive VV production. The VBF- W production study shows that the EW process is well modeled and can be enhanced in selected regions of phase space.

B. Zjj Production

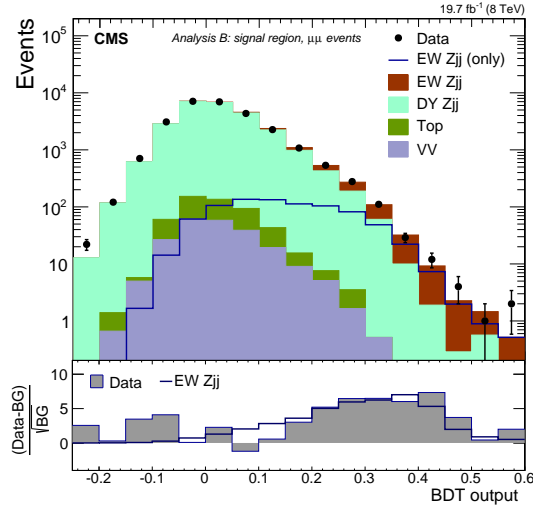
Electroweak production of a Z boson in association with two jets includes VBF Z boson production via the WWZ TGC and has been studied in the final state with a same-flavor, oppositely-charged lepton pair (electrons or muons) and two jets.

CMS has performed measurements (Chatrchyan *et al.*, 2013a; Khachatryan *et al.*, 2015a) at both 7 TeV and 8 TeV using data samples with integrated luminosities of 5 fb^{-1} and 20 fb^{-1} , respectively. In the 8 TeV analysis a Boosted Decision Tree (BDT) technique is used. As seen in Figure 27 (a), a BDT variable selection can be used to choose a region of phase space dominated by the EW process. The two major processes at high BDT values are EW and Drell-Yan (DY). Since the fit is normalized, the two processes are anti-correlated, as shown in Figure 27 (b). The magnitude of the EW cross section is found to be in agreement with theoretical NLO QCD predictions.

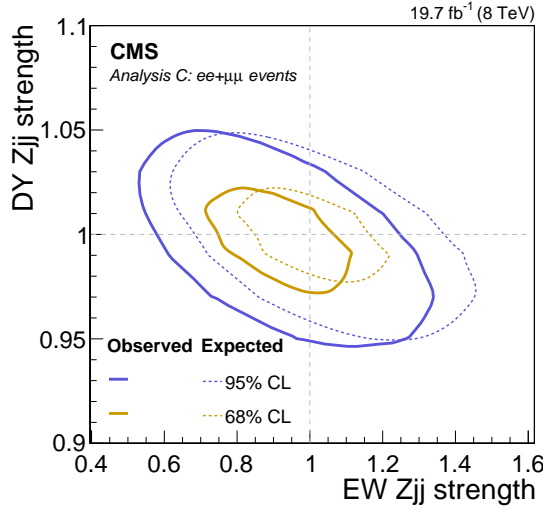
ATLAS has studied the $\ell\ell jj$ final state in 20 fb^{-1} of 8 TeV data (Aad *et al.*, 2014d) and uses a fit of the dijet invariant mass distribution with electroweak signal and QCD background templates to extract the electroweak production cross section in a fiducial region that enhances the signal contribution. The extracted signal is established with more than 5σ significance and the production rate is found to be in agreement with NLO SM predictions. In addition, cross sections and differential distributions are measured in five fiducial regions with different sensitivity to EW Zjj production, and limits on WWZ aTGCs λ_z and Δg_1^Z are placed based on the observed event yields in the tail of the dijet invariant mass distribution, shown in Figure 28.

VII. VECTOR BOSON SCATTERING

Vector Boson Scattering (VBS, $VV \rightarrow VV$) is an exclusive process wherein a constituent of each proton emits a boson which then interact with each other causing the



(a)

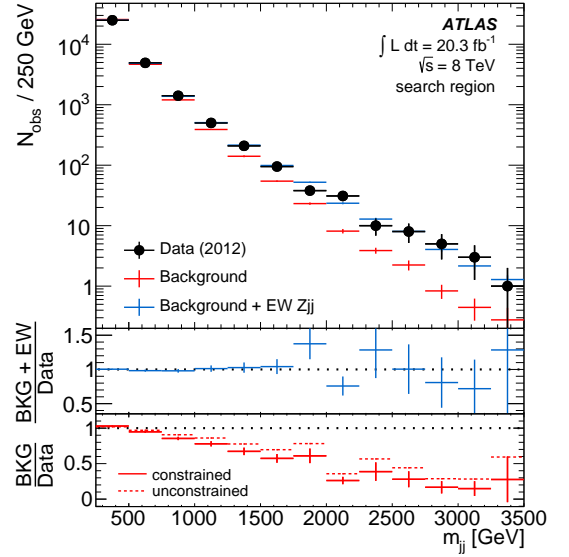


(b)

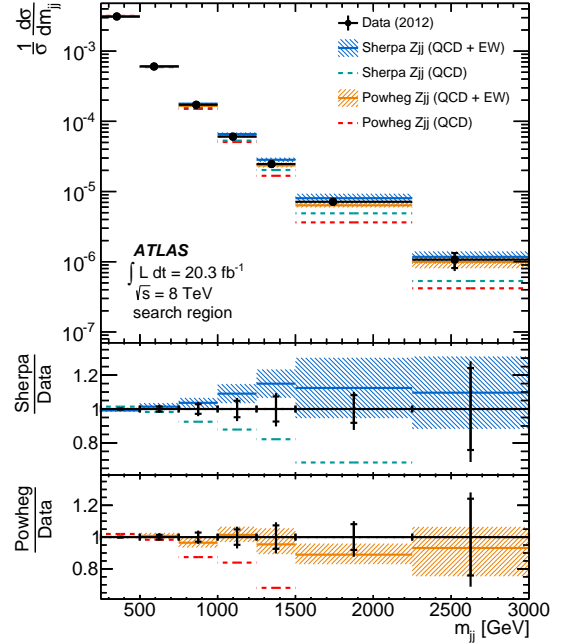
FIG. 27 (a) BDT output and Monte Carlo expectations for VBF-Z candidate events in the $\ell\ell jj$ final state at 8 TeV (Khachatryan *et al.*, 2015a). (b) Expected and observed 68% and 95% CL signal strength contours for EW and DY production of $\ell\ell jj$ at 8 TeV (Khachatryan *et al.*, 2015a).

emission of two new bosons. As in the case of VBF, the proton emission leads to remnant forward/backward or “tag” jets near to the initial beam directions with large rapidity difference and dijet mass. The resulting $VVjj$ final state ($V = \gamma, W^\pm, Z$) has contributions from both electroweak and QCD mediated processes. The latter can be suppressed by requiring the stated scattering topology. The electroweak processes include quartic boson self-interactions, whose amplitudes interfere with those of the other contributing diagrams, making a completely clean separation impossible.

One main argument for expecting new particles and/or interactions at the TeV scale is the linear divergence of the scattering amplitude for longitudinally polarized



(a)



(b)

FIG. 28 (a) Dijet invariant mass distribution of VBF-Z candidate events in the $\ell\ell jj$ final state at 8 TeV (Aad *et al.*, 2014d). (b) Unfolded normalized differential Zjj production cross section as a function of dijet invariant mass (Aad *et al.*, 2014d).

weak bosons as the center of mass energy squared increases (Lee *et al.*, 1977), which leads to the violation of unitarity at about 1 TeV. In the framework of the SM, this divergence is canceled through diagrams involving the exchange of a Higgs boson. Even if the recently discovered boson turns out to be the Higgs boson, its role in VBS still needs to be experimentally established to confirm the SM nature of EWSB. A wealth of mod-

els with dynamical EWSB in lieu of or in addition to the Higgs mechanism exists, making the measurement of VBS both a fundamental test of the SM and a window to new physics.

A. $W^\pm V jj$ Production

The study of the semileptonic WV ($V = W, Z$) VBS process benefits from the large hadronic branching fraction of the W or Z boson compared to the leptonic decays and the ability to fully reconstruct the WW contribution up to a quadratic ambiguity, resulting in improved sensitivity to anomalous event kinematics. Searching for anomalous quartic couplings in the high-mass tail of the WV spectrum is facilitated by the continually improving substructure techniques to analyze boosted monojets arising from the hadronically decaying V boson (see Figure 5). The $W^\pm V jj$ semileptonic final state includes contributions from the $W^\pm W^\mp jj$, $W^\pm W^\pm jj$ and $W^\pm Z jj$ VBS processes.

Building on the semileptonic WV decay signature described in Section IV.E with one charged lepton (electron or muon), missing transverse energy and exactly two jets in the final state, the corresponding VBS processes can be studied by requiring in addition the presence of a tagging jet pair with large invariant mass.

ATLAS (Aaboud *et al.*, 2016g) has performed a first search for anomalous couplings in $W^\pm V jj$ semileptonic VBS candidate events at 8 TeV using a data sample with an integrated luminosity of 20 fb^{-1} . While the extraction of the SM signal cross section is not yet possible due to large background contributions from W +jets and $t\bar{t}$ production, the analysis is optimized for aQGC sensitivity in a phase space where the SM contributions are sufficiently suppressed. The hadronic weak boson decay is reconstructed either via two jets in a “resolved” event category (which is split by lepton charge) or via a large monojet in a “merged” event category.

No excess is observed in the data, and the transverse mass distribution of the WV system in the two resolved and one merged event categories is used to constrain dimension eight operators with couplings α_4 , α_5 . Two of the observed distributions are shown in Figure 29 with the data extending to about 0.9 TeV in transverse mass. The obtained limits are more stringent than those obtained in the separate analyses of $W^\pm W^\mp jj$ and $W^\pm Z jj$ leptonic final states described in the following two sections. Given the largest sensitivity to aQGCs in the tail of the transverse mass distribution, the merged event category presently improves the expected sensitivity by about 40% compared to the resolved categories alone.

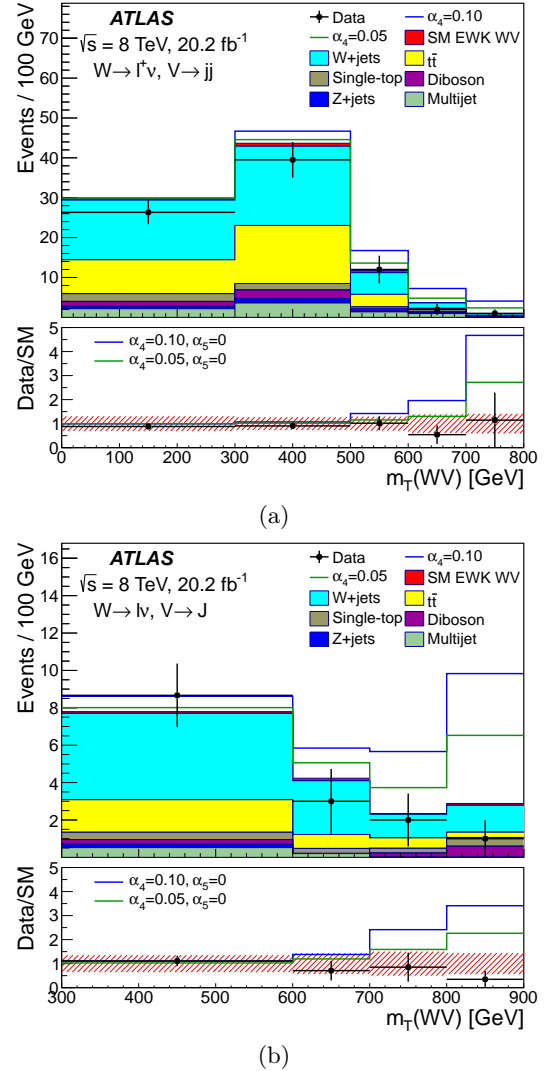


FIG. 29 $W^\pm V jj$ candidate event transverse diboson mass distributions in the $\ell^\pm \nu$ (jj/J) jj final state at 8 TeV (Aaboud *et al.*, 2016g): (a) resolved ($V \rightarrow jj$) category for positively charged leptons and (b) merged ($V \rightarrow J$) category. The potential impact of aQGCs is shown as well.

B. $W^\pm W^\pm jj$ Production

The production of same-sign W boson pairs in association with two jets includes the SM QGC contribution from the $WWWW$ vertex and is particularly valuable for the study of VBS processes with massive bosons since the strong production mode does not dominate over the electroweak mode of interest as is the case for the other $VVjj$ ($V = W, Z$) processes. The best signal to background ratio is achieved when studying the leptonic W boson decays, giving rise to final states with two leptons of the same sign (e or μ), MET and two jets.

Both ATLAS (Aad *et al.*, 2014c) and CMS (Khachatryan *et al.*, 2015i) have studied this final state in 8 TeV data samples with integrated luminosities of up

to 20 fb^{-1} , requiring the two leading (“tag”) jets to exhibit a large dijet invariant mass and to be well-separated in rapidity to enhance the VBS contribution (see Figures 30 (a) and 31). ATLAS and CMS find evidence for electroweak $W^\pm W^\pm jj$ production with 3.6 and 2.0σ significance, respectively, compatible with SM NLO expectations.

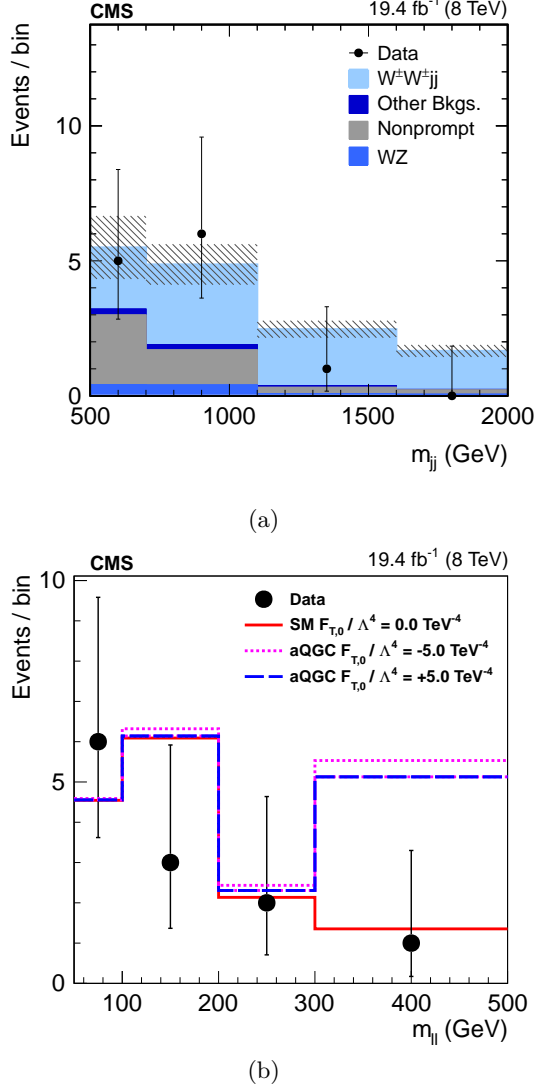


FIG. 30 VBS- $W^\pm W^\pm$ candidate events in the $\ell^\pm \nu \ell^\pm \nu jj$ final state at 8 TeV (Khachatryan *et al.*, 2015i): (a) dijet mass of the “tag” jets and (b) dilepton mass distribution, where the effect of a representative aQGC on the spectrum is also shown.

To constrain possible aQGC contributions, the measured cross section in the VBS fiducial region (ATLAS) or the dilepton mass shape is used (CMS, see Figure 30 (b)), where the data extend to about 0.5 TeV in dilepton mass. Dimension eight operators with couplings α_4 , α_5 or alternatively $f_{S0,1}$, $f_{M0,1,6,7}$ and $f_{T0,2}$ are probed.

ATLAS (Aaboud *et al.*, 2016e) has published in addition a detailed writeup of a re-analysis of the same data

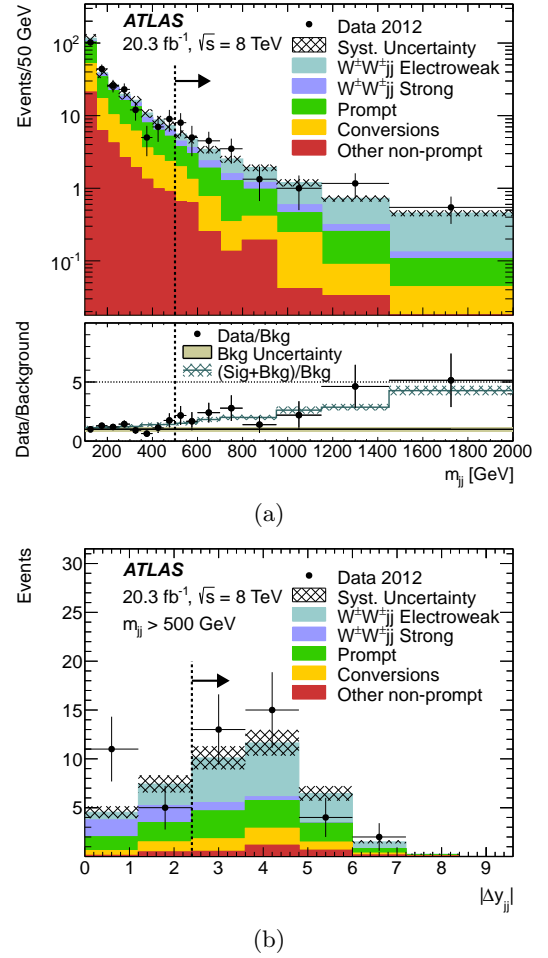


FIG. 31 VBS- $W^\pm W^\pm$ candidate events in the $\ell^\pm \nu \ell^\pm \nu jj$ final state at 8 TeV (Aad *et al.*, 2014c): (a) dijet mass and (b) rapidity separation of the “tag” jets. The applied selections are indicated by dotted lines.

set, where the sensitivity to anomalous couplings was optimized through an additional cut on the estimated transverse mass of the WW system. As a result, the expected α_4 , α_5 sensitivity is improved by 35% with respect to the previous analysis (Aad *et al.*, 2014c). Upper limits on the cross section in the resulting fiducial volume are provided as well.

C. $W^\pm Z jj$ Production

The production of $W^\pm Z$ boson pairs with two jets includes the SM QGC contribution from the $WZWZ$ and $W\gamma WZ$ vertices. The best signal to background ratio is achieved when studying the leptonic boson decay modes involving electrons and muons, resulting in a final state with three charged leptons, MET and at least two jets.

ATLAS has performed a first measurement in this final state at 8 TeV using a data sample with an integrated luminosity of 20 fb^{-1} (Aad *et al.*, 2016f). Requiring a

large invariant mass of the two leading “tag” jets, 95% CL limits on electroweak $W^\pm Z jj$ production are placed about a factor 4.8 higher than the SM cross section expectation at NLO in QCD in the fiducial volume under study, consistent with the expected sensitivity.

Additional selection criteria are applied to the data in order to optimize the expected sensitivity for aQGCs: Both a large difference in azimuthal angle between reconstructed W and Z boson directions and a large scalar sum of the p_T of the three charged leptons are required, with the distributions prior to the cuts shown in Figure 32. The resulting measured fiducial cross section is used to constrain dimension eight operators with couplings α_4 , α_5 or alternatively $f_{S0,1}$.

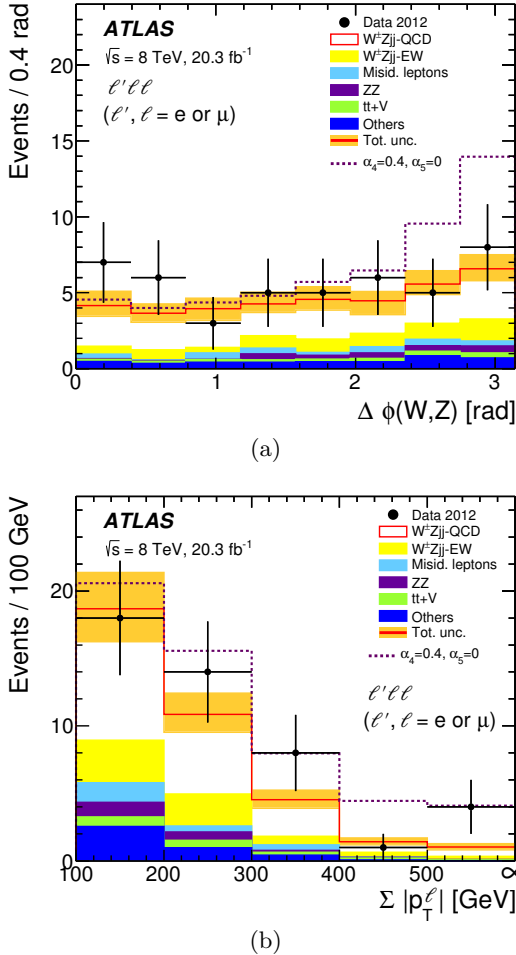


FIG. 32 Electroweak $W^\pm Z jj$ candidate event distributions in the $\ell^\pm \nu \ell^\pm \ell^\mp jj$ final state at 8 TeV (Aad *et al.*, 2016f): (a) difference in azimuthal angle between reconstructed W and Z boson directions and (b) scalar sum of the p_T of the three charged leptons. The potential impact of aQGCs is shown as well.

D. exclusive WW Production

Exclusive production of a W boson pair, $pp \rightarrow W^+ W^- pp$, proceeds via the emission of photons from the beam protons, which then interact to yield the W boson pair: $\gamma\gamma \rightarrow W^+ W^-$. In the elastic case, both protons remain intact after the interaction, while in the case of single (double) dissociation one (both) of the protons dissociate. In either case, the proton (remnants) closely follow the original beam direction and hence escape detection, leaving only the W boson decay products in the detector without the additional activity present in inclusive processes. The production of $W^+ W^-$ from photon scattering gives access to the SM QGC from the $WW\gamma\gamma$ vertex. The $WW\gamma\gamma$ coupling is the sole SM QGC contribution to the process since no “tag” jets indicating beam breakup are allowed which suppresses the $WWWW$, $WWZZ$ and $WWZ\gamma$ processes.

The best signal to background ratio is achieved when studying different-flavor leptonic W boson decays, giving rise to a final state with one electron and one muon of opposite charge and MET. ATLAS has performed a measurement (Aaboud *et al.*, 2016a) based on the full 20 fb^{-1} of its 8 TeV data set, while CMS utilizes both 7 TeV and 8 TeV data samples with integrated luminosities of 5 fb^{-1} and 20 fb^{-1} , respectively (Chatrchyan *et al.*, 2013g; Khachatryan *et al.*, 2016a). Exclusive events are selected by requiring no additional charged particles be present at the $e\mu$ vertex and a large p_T of the $e\mu$ pair.

ATLAS measures the exclusive $W^+ W^-$ cross section in good agreement with SM expectation with a significance of 3.0σ . Figure 33 (a) shows the distribution of the difference in azimuthal angle between electron and muon, clearly indicating the need for the signal contribution to describe the observed data. First upper limits on exclusive Higgs boson production in the $H \rightarrow WW$ decay mode are provided as well, based on a separately optimized selection.

CMS places an upper limit on $\gamma\gamma \rightarrow W^+ W^-$ production in the 7 TeV analysis, corresponding to about 2.6 times the SM theoretical expectation at 95% CL, while at 8 TeV first evidence for the signal is observed with a significance of 3.2σ . Combining the 7 and 8 TeV data, the signal significance increases to 3.4σ . The $e\mu$ acoplanarity is shown in Figure 34 (a) in the 8 TeV data, indicating consistent yields with respect to signal and background expectations and a dominant VBS contribution.

Both ATLAS and CMS use the shape of the dilepton p_T distribution, shown in Figure 33 (b) and Figure 34 (b) for the 8 TeV data set, to limit aQGC dimension six operators with couplings a_0^W , a_C^W . Corresponding transformed limits on dimension eight operators with couplings $f_{M0.3}$ are provided as well.

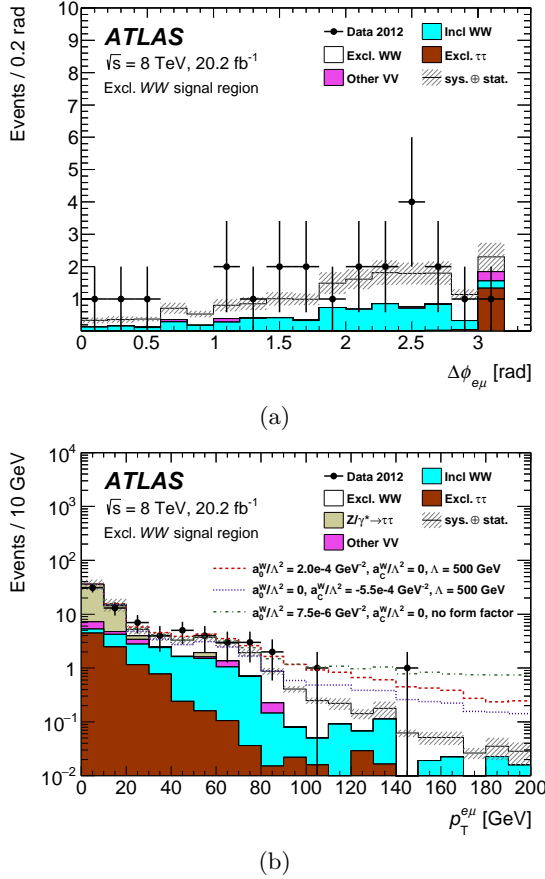


FIG. 33 VBS- $\gamma\gamma \rightarrow W^+W^-$ candidate events in the $e^\pm\nu\mu^\mp\nu$ final state in 8 TeV data (Aaboud *et al.*, 2016a): (a) difference in azimuthal angle between electron and muon and (b) dilepton p_T distribution before applying the 30 GeV selection cut. The potential impact of aQGCs is shown as well.

VIII. CONSTRAINTS ON ANOMALOUS TRIPLE GAUGE COUPLINGS

The exploration of high- \hat{s} diboson and VBF events leads to limits on possible triple gauge couplings which are differing from or not present in the SM: anomalous triple gauge couplings, aTGC. Limits on aTGC have been presented by experiments at LEP, the Tevatron and the LHC. aTGC limits arise when specific spectra of final state particles are compared to the expectations of the SM with additional aTGC terms in the Lagrangian. The specific spectra used at the LHC were shown in Sections IV, VI for aTGCs and Sections V, VII for aQGCs. It should be noted that higher order (NNLO QCD and NLO EW) corrections will significantly impact the SM expectation in the tails of the utilized distributions, and the incorporation of such corrections depends on the timing of the corrections becoming available versus when the analysis was carried out. The various limits made with different diboson and VBF final states are here collected and compared. Typically, one-dimensional (1-d) limits

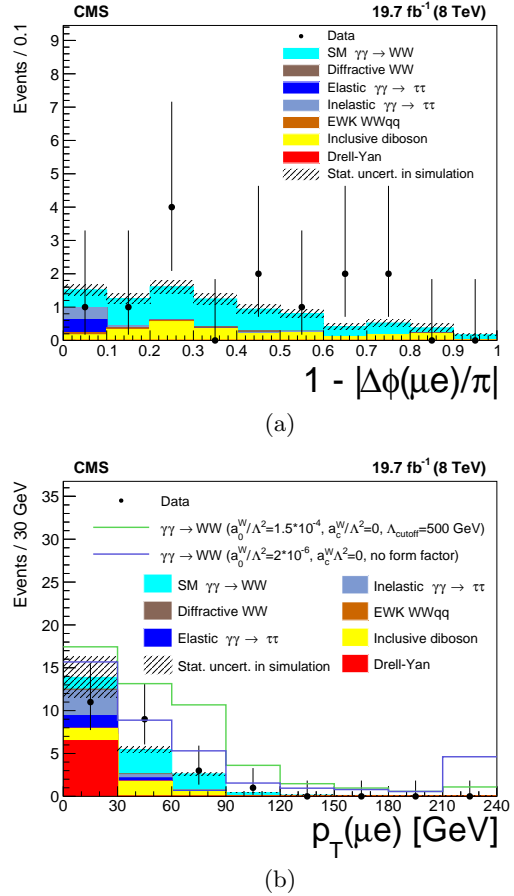


FIG. 34 VBS- $\gamma\gamma \rightarrow W^+W^-$ candidate events in the $e^\pm\nu\mu^\mp\nu$ final state in 8 TeV data (Khachatryan *et al.*, 2016a): (a) acoplanarity of the $e\mu$ system and (b) dilepton p_T distribution before applying the 30 GeV selection cut. The potential impact of aQGCs is shown as well.

are quoted where only one operator is allowed to be non-zero at a time. In a few cases two operators are allowed to float simultaneously, a procedure which illustrates the correlations between the effects of the operators.

In the SM there are $WW\gamma$ and WWZ TGCs. They are studied in WW , WZ , $W\gamma$, VBF- W and VBF- Z final states. Beyond the SM there are ZZZ , $ZZ\gamma$, $Z\gamma Z$, $Z\gamma\gamma$ and $\gamma\gamma\gamma$ couplings, where limits on the first four are placed by exploring ZZ and $Z\gamma$ final states. In the future, with higher luminosity data taking, the $\gamma\gamma$ final state, Section IV.A, can be used to explore the non-SM $\gamma\gamma\gamma$ aTGC.

A. $WW\gamma$ and WWZ limits

WWZ and $WW\gamma$ limits can be formulated with aTGC as was done in other prior experiments at LEP (ALEPH, DELPHI, L3, and OPAL) and the Tevatron (CDF and D0). The five independent C- and P-conserving aTGC

parameters that remain after imposing electromagnetic gauge invariance, $\Delta g_1^Z (\equiv g_1^Z - 1)$, $\Delta \kappa_Z (\equiv \kappa_Z - 1)$, $\Delta \kappa_\gamma (\equiv \kappa_\gamma - 1)$, λ_Z and λ_γ are all zero in the SM, and limits on all these parameters have been provided independently by recent LHC publications. In order to be able to compare limits from LHC, Tevatron and LEP on equal footing, results from the “LEP scenario” (Altarelli *et al.*, 1996; Gounaris *et al.*, 1996) are used, which are available from all experiments. Motivated by $SU(2) \times U(1)$ symmetry, the LEP scenario assumes $\Delta \kappa_\gamma = (\Delta g_1^Z - \Delta \kappa_Z) / \tan^2 \theta_W$, and $\lambda_\gamma = \lambda_Z$, thereby reducing the number of independent parameters to three.

Figure 35 shows a comparison of the most competitive limits derived in the LEP scenario by experiments at the LHC, Tevatron and LEP. The impact of imposing unitarity constraints on the anomalous couplings via a dipole form factor with a suppression scale Λ_{FF} that dampens the cross section increase at high \hat{s} for any anomalous coupling α with value α_0 at low energies, $\alpha(\hat{s}) = \alpha_0 / (1 + \hat{s} / \Lambda_{\text{FF}}^2)^2$, is shown as well. The LHC limits using WW and WZ final states for constraining $WW\gamma$ and WWZ couplings are already more stringent than the combined D0 or LEP limits. Presently, the higher energy and higher statistics data at 8 TeV give the strongest LHC limits. Increased luminosity and center of mass energy in Run II and beyond will further reduce the LHC limits.

The two-dimensional limits shown in Figure 36 illustrate the anti-correlation of the $\Delta \kappa^V$ and λ^V parameters when no constraints are assumed on the five aTGC parameters. Typically, only the 1-d limits are shown since the correlations are usually small.

More recently, the EFT formulation of possible aTGC in terms of dimension six operators for triple boson couplings has come into use. A marked difference with respect to the anomalous Lagrangian vertex couplings is that the EFT-based anomalous couplings are not valid to arbitrary energy scales, but instead are only valid below the scale Λ where new physics sets in. Using the same assumptions as in the LEP scenario and applying no unitarization, the aTGC parameters can be directly translated into EFT coefficients c_W , c_{WW} and c_B (Degrande *et al.*, 2013c).

Since these dimension six operators are not expected to lead to unitarity violation in diboson production at LHC center of mass energies (Degrande *et al.*, 2013c), the same must hold true for their aTGC counterparts. The reason that for example the ATLAS WW analysis (Aad *et al.*, 2016e) nevertheless gives aTGC unitarization bounds is that the used unitarity considerations in (Aihara *et al.*, 1995) are valid for *arbitrary center of mass energies*.

Figure 37 shows a comparison of the best aTGC limits, arising from WW and WZ analyses in leptonic final states by ATLAS and CMS using the full 8 TeV data sets and converted to the EFT formalism. Figure 38 illustrates the weak correlations between these EFT pa-

rameters.

B. $Z\gamma\gamma$ and $Z\gamma Z$ limits

Limits on the $Z\gamma\gamma$ and $Z\gamma Z$ couplings are usually given using the CP-conserving parameters h_3^V and h_4^V since there is no interference with the CP-violating couplings associated with the h_1^V and h_2^V parameters and the corresponding cross sections and sensitivities are very similar (Baur and Berger, 1993). Figure 39 shows a comparison of the most competitive limits, set by ATLAS and CMS. The combined limits by LEP (Schael *et al.*, 2013) as well as the best Tevatron limits by CDF (Aaltonen *et al.*, 2011) on h_3^V , h_4^V are not competitive with those achieved at the LHC. The impact of imposing unitarity constraints on the anomalous couplings via a form factor with a suppression scale Λ_{FF} , $\alpha(\hat{s}) = \alpha_0 / (1 + \hat{s} / \Lambda_{\text{FF}}^2)^n$, is shown as well. The form factor exponent n is equal to the index i of the parameter h_i^V under study (Baur and Berger, 1993), in contrast with the dipole form factor, $n = 2$, assumed in Section VIII.A. This illustrates the model dependence inherent in the form factor approach. In general, the parameter Λ_{FF} is chosen differently for different processes and the choice of the exponent n can also vary in the absence of a definitive prediction.

C. $ZZ\gamma$ and ZZZ limits

Turning to ZZ final states, the limits on anomalous triple gauge couplings are expressed in terms of two CP-violating (f_4^V) and two CP-conserving (f_5^V) parameters, all of which are zero in the SM. The limits on f_i^V are negatively correlated for a given i as illustrated in Figure 40 which is based on 7 TeV ZZ candidate events in the 4ℓ decay mode.

One-dimensional limits for the f_i^V parameters derived from ZZ final states are shown in Figure 41. The $2\ell 2\nu$ decay mode gives the most stringent limits due to increased branching fraction and detector acceptance. The 8 TeV data give significantly stronger limits on the f_i^V parameters, due to larger statistics and an extended reach in Z boson transverse momentum. The combined limits by LEP (Schael *et al.*, 2013) as well as the best Tevatron limits by D0 (Abazov *et al.*, 2008) are not competitive with those achieved at the LHC. The impact of imposing unitarity constraints on the anomalous couplings via a form factor, $\alpha(\hat{s}) = \alpha_0 / (1 + \hat{s} / \Lambda_{\text{FF}}^2)^3$, is shown as well. In this specific case the exponent $n = 3$ is chosen. Studying the sensitivity at 8 TeV, ATLAS (Aaboud *et al.*, 2016d) finds that a unitarization with a dipole form factor is no longer needed as the aTGC limits approach more and more the SM expectation (Gounaris *et al.*, 2000).

ATLAS and CMS have also performed a first combination of aTGC limits based on their 7 TeV ZZ analy-

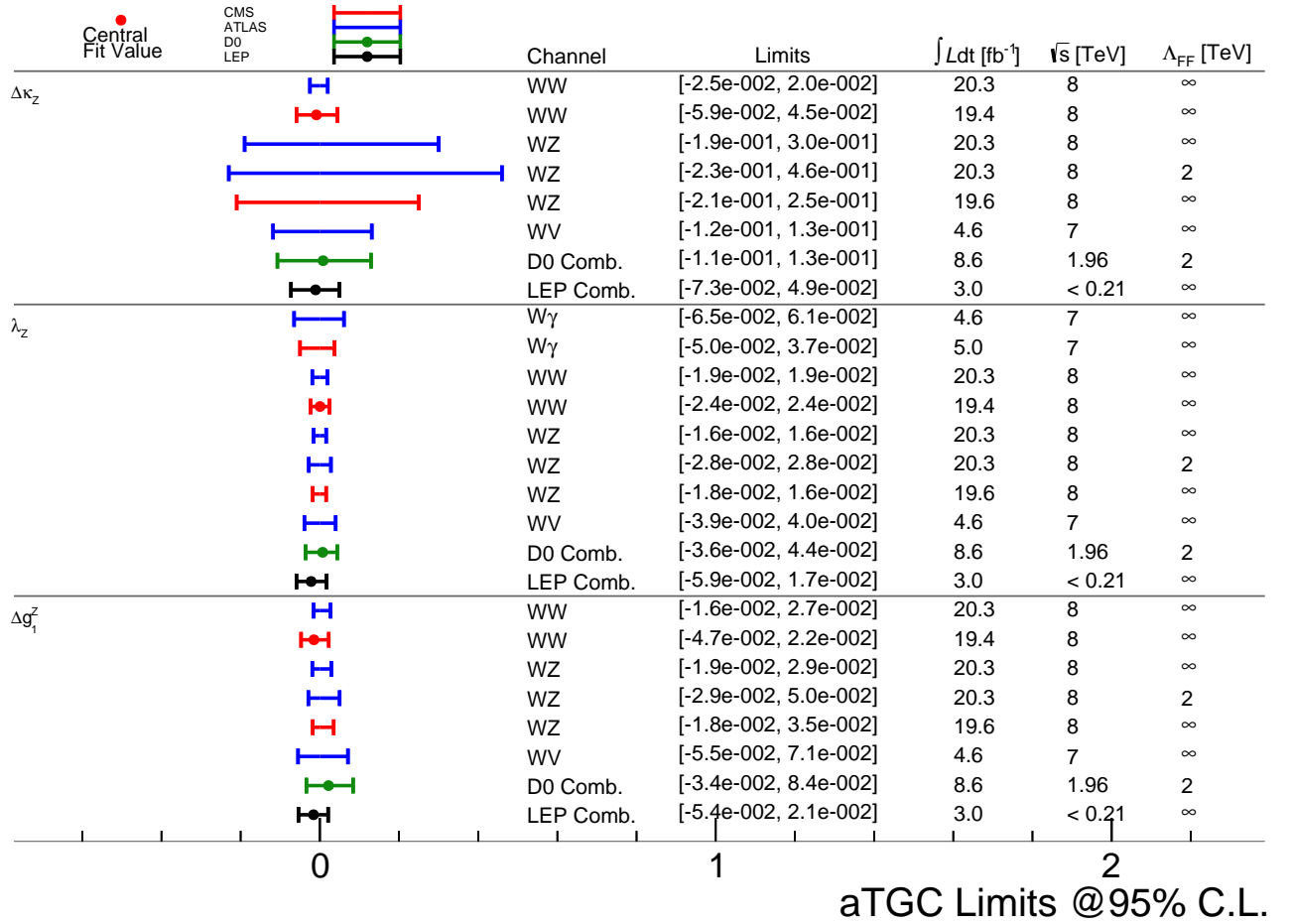


FIG. 35 Comparison of the most competitive aTGC limits in the LEP scenario for the LHC analyses presented in this review as well as the combination of limits by the D0 (Abazov *et al.*, 2012) and LEP (Schael *et al.*, 2013) experiments.

ses (Aad *et al.*, 2016a). With a negligible impact due to systematic uncertainties, the combination improves the aTGC sensitivity by about 20 % compared to the sensitivity of each experiment. While the resulting limits are not competitive with the 8 TeV results presented above, this is an important first step towards future combined LHC limits on anomalous couplings.

IX. CONSTRAINTS ON ANOMALOUS QUARTIC GAUGE COUPLINGS

In the SM there are $WWWW$, $WWZZ$, $WWZ\gamma$ and $WW\gamma\gamma$ couplings. Beyond the SM there are possible $ZZZZ$, $ZZZ\gamma$, $ZZ\gamma\gamma$, $Z\gamma\gamma\gamma$ and $\gamma\gamma\gamma\gamma$ couplings as listed in Table I. In Run I ATLAS and CMS have only begun to investigate a few of these possible couplings, with much more data planned in Run II and beyond.

The aQGC limits follow from the examination of the production of inclusive triple gauge bosons, VBS dibosons and exclusive dibosons. The limits are generally taken to be limits on the coefficients of dimension eight

operators (Éboli *et al.*, 2006), f , although with assumptions (Chatrchyan *et al.*, 2014e) some of these are related to an equivalent set, a , of dimension six operators (Belanger and Boudjema, 1992; Éboli *et al.*, 1994; Stirling and Werthenbach, 2000), commonly used in Tevatron and LEP analyses. Table I lists the 18 different dimension eight operators and which quartic vertex they affect. Note that these operators do not include TGCs.

The LEP L3 and OPAL experiments have set their best aQGC limits by combining $W^+W^-\gamma$, $\nu\bar{\nu}\gamma\gamma$ (Achard *et al.*, 2002) and $W^+W^-\gamma$, $\nu\bar{\nu}\gamma\gamma$, $q\bar{q}\gamma\gamma$ (Abbiendi *et al.*, 2004) analyses, respectively. These limits are surpassed by Tevatron's D0 experiment using the exclusive VBS process, $\gamma\gamma \rightarrow WW$ (Abazov *et al.*, 2013). Since the early LHC results are already considerably more restrictive than the LEP and Tevatron limits, they are not shown in the following comparisons.

The $W\gamma\gamma$ data is affected only by the SM $WW\gamma\gamma$ coupling, while $WV\gamma$ data has contributions owing to $WW\gamma\gamma$ and $WWZ\gamma$ couplings. The VBS $WZjj$ data is affected by the SM $WWZZ$ and $WWZ\gamma$ couplings. The $WWWW$ and same-sign WW VBS data selects only the

	WWWW	WWZZ	WW γ Z	WW $\gamma\gamma$	ZZZZ	ZZZ γ	ZZ $\gamma\gamma$	Z $\gamma\gamma\gamma$	$\gamma\gamma\gamma\gamma$
$\mathcal{O}_{S,0}, \mathcal{O}_{S,1}$	✓	✓			✓				
$\mathcal{O}_{M,0}, \mathcal{O}_{M,1}, \mathcal{O}_{M,6}, \mathcal{O}_{M,7}$	✓	✓	✓	✓	✓	✓	✓		
$\mathcal{O}_{M,2}, \mathcal{O}_{M,3}, \mathcal{O}_{M,4}, \mathcal{O}_{M,5}$		✓	✓	✓	✓	✓	✓		
$\mathcal{O}_{T,0}, \mathcal{O}_{T,1}, \mathcal{O}_{T,2}$	✓	✓	✓	✓	✓	✓	✓	✓	✓
$\mathcal{O}_{T,5}, \mathcal{O}_{T,6}, \mathcal{O}_{T,7}$		✓	✓	✓	✓	✓	✓	✓	✓
$\mathcal{O}_{T,8}, \mathcal{O}_{T,9}$					✓	✓	✓	✓	✓

TABLE I Dimension eight operators and the quartic vertices they affect (Degrande *et al.*, 2013b). The first four columns show the only QGC vertices which exist in the SM.

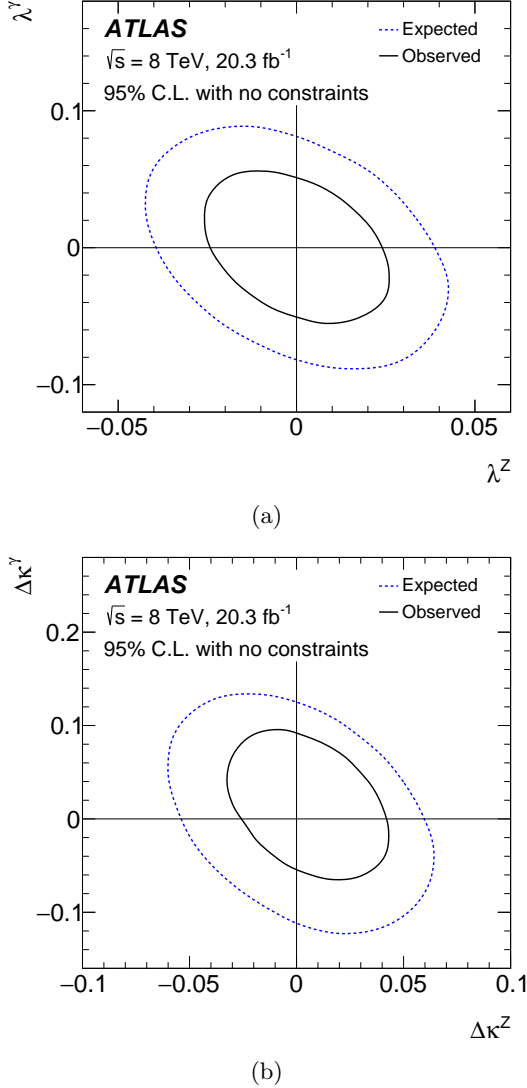


FIG. 36 Expected and observed 95% C.L. contours for aTGC limits derived from 8 TeV fully leptonic WW candidate events (Aad *et al.*, 2016e), illustrating the anti-correlations between (a) λ^V and (b) $\Delta\kappa^V$ parameters when no constraints between aTGCs are assumed. The aTGCs not shown are set to zero.

SM $WWWW$ coupling while the exclusive $\gamma\gamma \rightarrow WW$ data selects only the SM $WW\gamma\gamma$ coupling. Finally, the VBS $WVjj$ data is affected by all SM quartic couplings.

The one-dimensional limits on the EFT coefficients $f_{T,i}$ for dimension-eight operators containing just the field strength tensors are shown in Figure 42. The VBS diboson channels yield similar limits, which are better than the triple boson production limits.

The ATLAS $W\gamma\gamma$ and $Z\gamma\gamma$ results are derived with VBFNLO MC samples, which use a different convention for the dimension-eight operators than the corresponding CMS results derived with MadGraph5_aMCNLO MC samples. To be able to compare the results with CMS, the ATLAS results were converted using the redefinition of operator coefficients outlined in (Degrande *et al.*, 2013b).

The impact of imposing unitarity constraints on the anomalous couplings via a dipole form factor with a suppression scale Λ_{FF} is shown as well. It should be noted that the impact of unitarization is much larger than in case of the aTGCs. Limits without unitarization hence clearly probe a regime where unitarity is violated at the scales probed and are more a benchmark than physically meaningful.

The analogous plot of limits for the $f_{M,i}$ coefficients for “mixed” dimension-eight operators containing covariant derivatives and the field strength tensors are shown in Figure 43. Again, the VBS diboson channels are all comparable and yield the tightest limits although generally the same-sign WW limits are the most stringent. Where the exclusive process $\gamma\gamma \rightarrow WW$ is used to set a limit it is the most stringent, because the signal is so clean that it dominates the final selected data. The sensitivity of ATLAS and CMS to anomalous couplings is generally very similar. Limits on $f_{M,2}$ and $f_{M,3}$ were not included in the summary when they are trivially related to $f_{M,0}$ and $f_{M,1}$ by a factor of two under the assumption of a vanishing anomalous $WWZ\gamma$ coupling (Khachatryan *et al.*, 2016a). The ATLAS $W\gamma\gamma$ and $Z\gamma\gamma$ results are again converted to the convention employed by CMS, using the relations given in (Degrande *et al.*, 2013b). The $WV\gamma$ and $\gamma\gamma \rightarrow WW$ results are based on the dimension-six operators with coefficients $a_{0,C}^W$ which are then converted to dimension-eight operators with coefficients $f_{M,0}$ and $f_{M,1}$. The conversion conventions em-

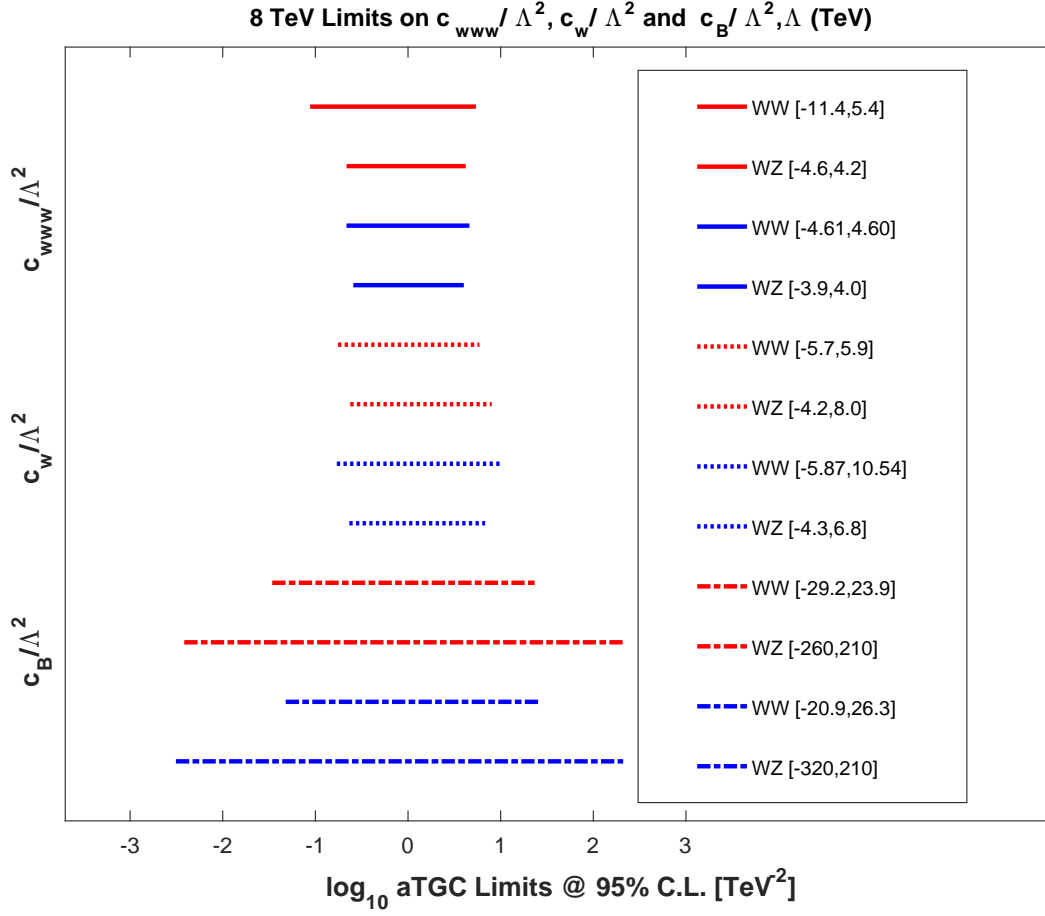


FIG. 37 Comparison of the most competitive aTGC EFT limits based on the 8 TeV WW and WZ analyses in leptonic final states by ATLAS (blue) and CMS (red), using the full available data sets.

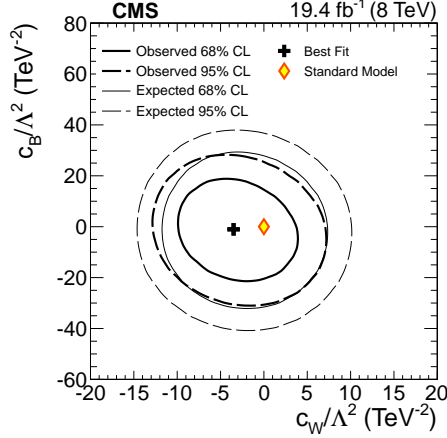


FIG. 38 Expected and observed 68% and 95% C.L. contours for aTGC limits in the EFT formulation derived from 8 TeV fully leptonic WW candidate events (Khachatryan *et al.*, 2015c) illustrating the weak correlations between these EFT parameters, with c_{WWW} set to zero.

ployed by ATLAS (Degrande *et al.*, 2013b) and CMS (Belanger *et al.*, 2000) differ because CMS implemented their own Lagrangians in `MadGraph5_aMCNLO` for $WV\gamma$ and $\gamma\gamma \rightarrow WW$. To enable comparisons, the results from these two analyses and the ATLAS $\gamma\gamma \rightarrow WW$ analysis are derived from their $a_{0,C}^W$ results using the conversion in (Degrande *et al.*, 2013b) to give results following the standard `MadGraph5_aMCNLO` convention.

The impact of imposing unitarity constraints on the anomalous couplings via a dipole form factor with a suppression scale Λ_{FF} is shown as well. Again, unitarization can change some of the limits by orders of magnitude for these dimension-eight operators, indicating that such limits without unitarization are driven by unphysical parameter regions where unitarity is violated.

Limits on the $f_{S,i}$ coefficients whose operators affect the scattering of longitudinal vector bosons have been placed by the CMS same-sign WW and ATLAS WWW analyses and are summarized in Figure 45, illustrating the impact of applying unitarization with a form factor exponent $n = 1$.

The $W^\pm Vjj$, $W^\pm W^\pm jj$ and $W^\pm Zjj$ results by ATLAS are not included in the above summary plots since they set limits on the parameters $\alpha_{4,5}$ in an electroweak chiral Lagrangian model (Appelquist and Bernard, 1980; Appelquist and Wu, 1993; Longhitano, 1980, 1981) with K-matrix unitarization (Alboreanu *et al.*, 2008; Kilian *et al.*, 2015) applied. While vertex-dependent conversions to $f_{S,0}$ and $f_{S,1}$ exist (Degrande *et al.*, 2013b), for the $W^\pm Vjj$ analysis multiple vertices contribute. Consequently, the resulting limits are summarized separately in Figure 44.

The introduction of an additional dimension-eight operator $\mathcal{O}_{S,2}$ (Éboli and GonzalezGarcia, 2016) enables the vertex-independent conversion to the parameters

$\alpha_{4,5}$ when considering quartic gauge-boson vertices only, through the study of a linear combination of $\mathcal{O}_{S,2}$ and $\mathcal{O}_{S,0}$ (Rauch, 2016). This would be highly desirable for future studies, and it should be noted that these resulting conversions are also applicable *after* K-matrix unitarization (Sekulla *et al.*, 2016).

In order to be able to compare the analyses on equal footing, we use the conversion for the WWW vertex for the CMS same-sign WW and ATLAS WWW analyses, omitting the results unitarized with a form-factor as the applicability of the conversion is then questionable. The resulting comparison is given in Figure 46, with the relative sensitivities to be taken with a grain of salt when no unitarization is applied.

It should be noted that the $W^\pm Vjj$ analysis is the first semi-leptonic VBS analysis and exhibits a high sensitivity to anomalous couplings due to the larger branching fraction as well as probing the three distinct processes $W^\pm W^\mp jj$, $W^\pm W^\pm jj$ and $W^\pm Zjj$. It yields the most stringent unitarized limits thus far of $-0.024 < \alpha_4 < 0.030$ and $-0.028 < \alpha_5 < 0.033$ at 95% C.L., corresponding to a new physics scale above ≈ 1.4 TeV when assuming $\alpha_i = v^2/\Lambda^2$ (Reuter *et al.*, 2013), where v is the Higgs vacuum expectation value ($v \approx 246$ GeV).

X. SENSITIVITY PROSPECTS AT THE HL-LHC

Both the updated European Strategy for Particle Physics (Council, 2013) and the Particle Physics Project Prioritization Panel (P5) report (Ritz *et al.*, 2014) outlining a ten-year strategic plan for HEP in the US emphasize the use of the full LHC potential through a high-luminosity upgrade (HL-LHC) as top priority for the field. An important ingredient for the physics case are the detailed studies of multi-boson interactions which enable the test of the EWSB mechanism as well as the search for extensions beyond the SM.

The Physics Briefing Book (Aleksan *et al.*, 2013) for the European Strategy for Particle Physics points out that studies of longitudinal VBS to explore the EWSB mechanism in detail will not be possible without the HL-LHC data set. As an example for the enhanced sensitivity achievable with the HL-LHC to unveil new phenomena, a study by ATLAS (Aad *et al.*, 2012m) using simplified detector performance parameterizations is shown, where a new physics VBS ZZ resonance could only be discovered using the HL-LHC data set.

For the snowmass community study preceding the P5 formation, both ATLAS (Aad *et al.*, 2013g) and CMS (CMS, 2013) provided contributions which outline the physics program as well as sensitivity improvements at the HL-LHC. With the enhanced data set, diboson differential cross section measurements in the high \hat{s} tails of distributions will be possible as well as detailed studies of VBF, VBS and triboson production, from establish-

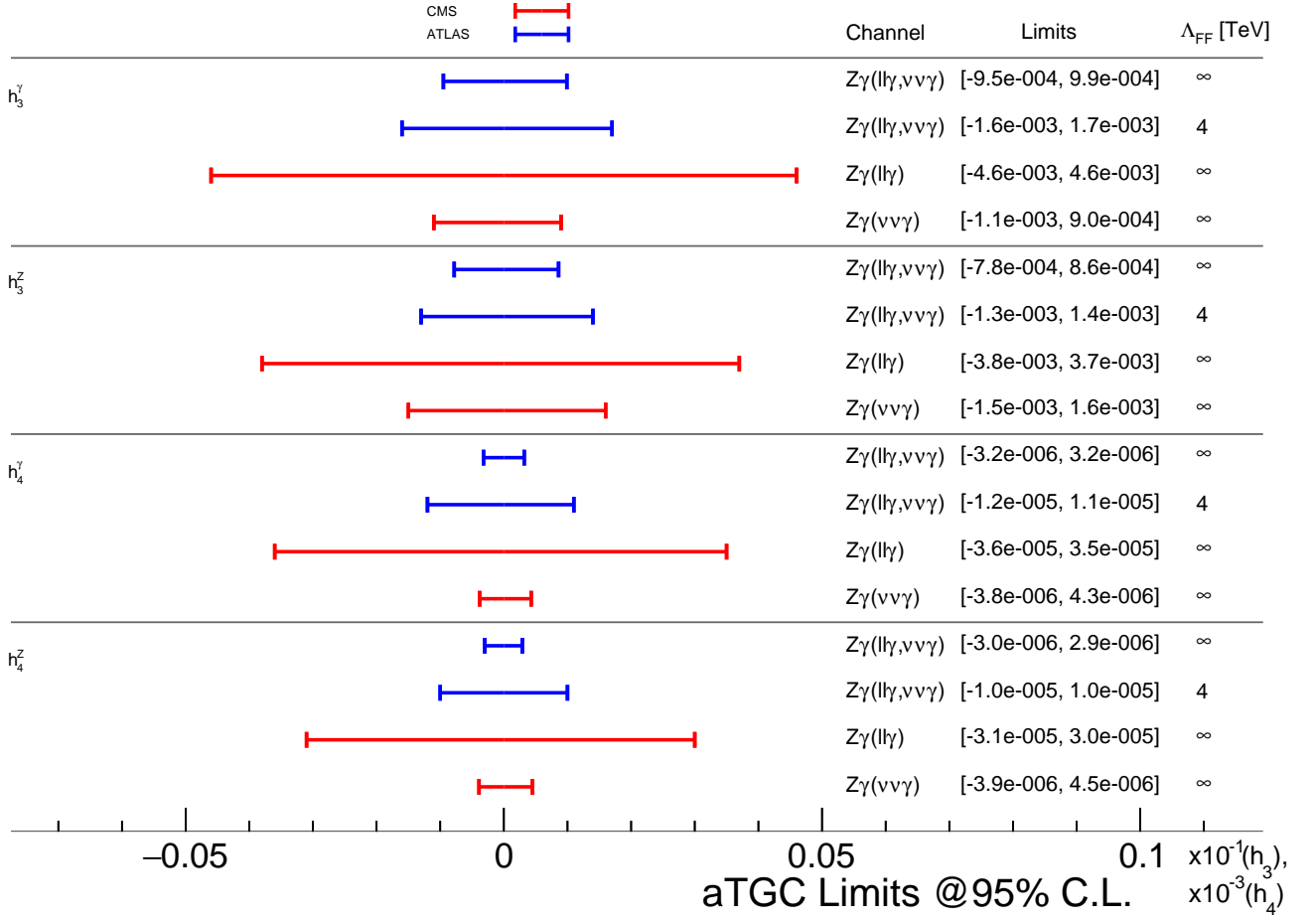


FIG. 39 Comparison of the most competitive $Z\gamma\gamma$ and $Z\gamma Z$ limits, set by the LHC analyses presented in this review. All limits are based on the full 8 TeV, $\approx 20 \text{ fb}^{-1}$ data sets.

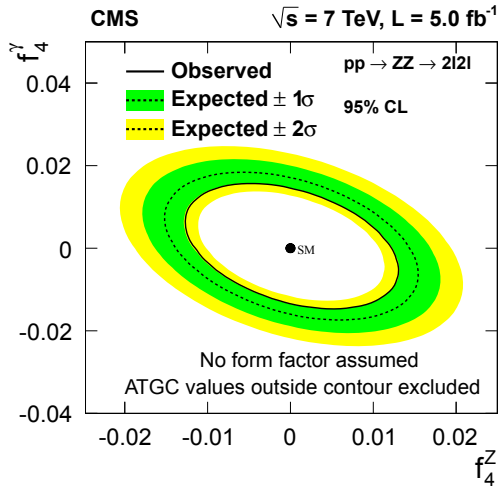


FIG. 40 Expected and observed 95% C.L. contours for aTGC limits derived from 7 TeV ZZ candidate events in the 4ℓ decay mode (Chatrchyan *et al.*, 2013e) for the f_4^γ versus f_4^Z parameters. aTGCs not shown are set to zero.

ing the signals to measuring differential cross sections with high precision. The discovery reach for new higher-dimensional operators studied in $W^\pm W^\pm$, WZ , ZZ VBS processes and $Z\gamma\gamma$ is at least doubled in the HL-LHC data set (Aad *et al.*, 2013h). The proceedings of the snowmass community study (Bardeen *et al.*, 2013) also quantify the dimension-eight operator sensitivity increase due to the HL-LHC to be a factor of two to three over the LHC, based on independent studies (Baak *et al.*, 2013; Degrande *et al.*, 2013a) of $W^\pm W^\pm$, WZ , ZZ VBS processes and WWW , $Z\gamma\gamma$ triboson production.

Both ATLAS and CMS are preparing major detector upgrades for the HL-LHC and have used VBS interactions as a benchmark for the anticipated performance (Aad *et al.*, 2015a; Khachatryan *et al.*, 2015j). Extended tracking systems will enable improved lepton identification also in the forward detector regions as well as crucial suppression of pileup jet contributions to the tagging jet signature.

Measuring the polarization fractions in VBS is a crucial experimental test of the predicted unitarization of the longitudinal VBS cross section by the SM Higgs bo-

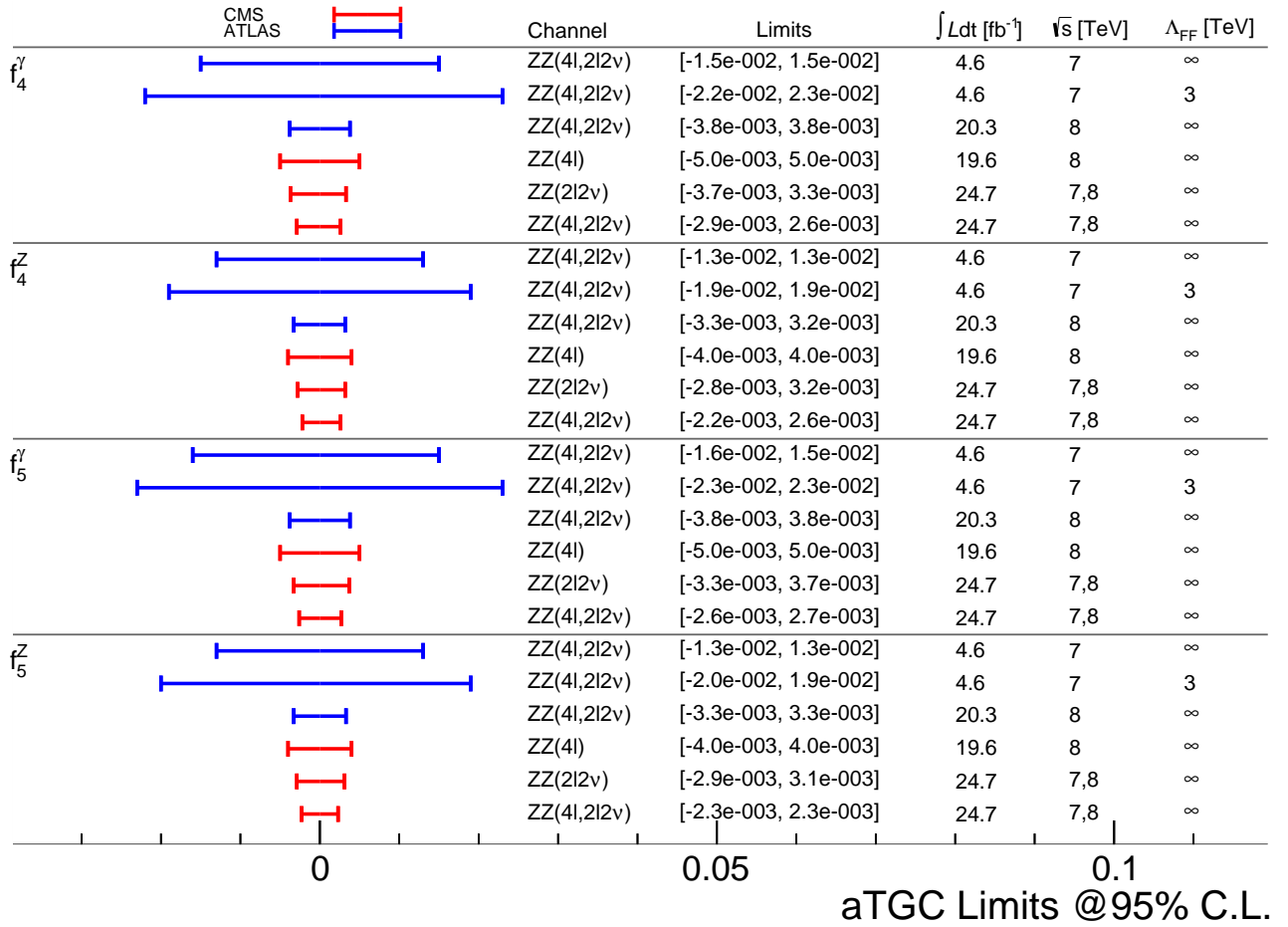


FIG. 41 Comparison of the most competitive $ZZ\gamma$ and ZZZ limits, set by the LHC analyses presented in this review.

son. CMS (Khachatryan *et al.*, 2015j) has evaluated the expected sensitivity to measure the longitudinal fraction in $W^\pm W^\pm$ scattering using a two-dimensional template fit of the $\Delta\Phi$ between the two tagging jets and the p_T of the leading lepton and expect a significance of $\approx 2.4\sigma$ in the HL-LHC data set as illustrated in Figure 47 (a). Combining this with a corresponding WZ VBS analysis, the longitudinal VBS significance increases to 2.75σ . It should be noted that a significant increase in sensitivity should still be possible using a deep machine learning technique instead of a “simple” variable fit, as demonstrated for the $W^\pm W^\pm$ VBS case in (Searcy *et al.*, 2015).

The HL-LHC data set will also greatly enhance the sensitivity to anomalous couplings. Figure 47 (b) shows the expected dilepton mass distribution in $W^\pm W^\pm$ VBS candidate events with 3000 fb^{-1} , where the data extend to about 1.5 TeV. This is a factor of three higher than accessible in Run I and will improve the aQGC limits by about a factor of 50 for the aQGC example shown.

The search for new physics contributions in multi-boson interactions either indirectly through anomalous

couplings or directly through resonance searches will greatly benefit from the increased exploitation of final states with hadronically decaying W/Z bosons. To probe the high-mass tail of the VV spectrum, this means the identification of merged dijets into boosted monojets (the hadronically decaying V boson) will be of crucial importance (Aad *et al.*, 2016b; Khachatryan *et al.*, 2014b), in particular at the HL-LHC (see Figure 5).

With the advent of first analyses in the Higgs sector employing the EFT approach (Aad *et al.*, 2016c) rather than the κ framework (Andersen *et al.*, 2013) which allows the modification of Higgs couplings without affecting its kinematics, combined constraints from the Higgs and multi-boson analyses will be possible. Such analyses will properly reflect the interconnectedness of multi-boson and Higgs interactions in EFTs and yield improved constraints, as has been demonstrated by external global fits (Butter *et al.*, 2016; Corbett *et al.*, 2013; Ellis *et al.*, 2015; Falkowski and Riva, 2015; Pomarol and Riva, 2014).

To benefit from the tremendous progress in the theoretical predictions it will be important to perform mea-

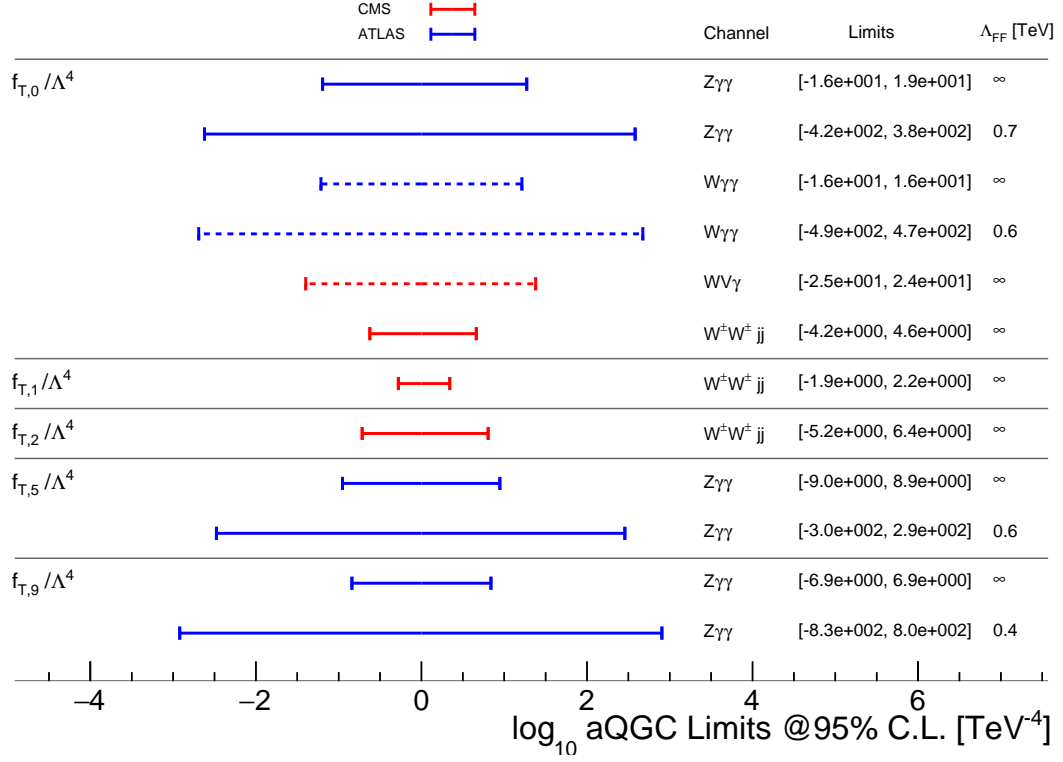


FIG. 42 Comparison of the most competitive limits involving $f_{T,i}$ coefficients, set by the LHC analyses presented in this review. All limits are based on the full 8 TeV, $\approx 20 \text{ fb}^{-1}$ data sets.

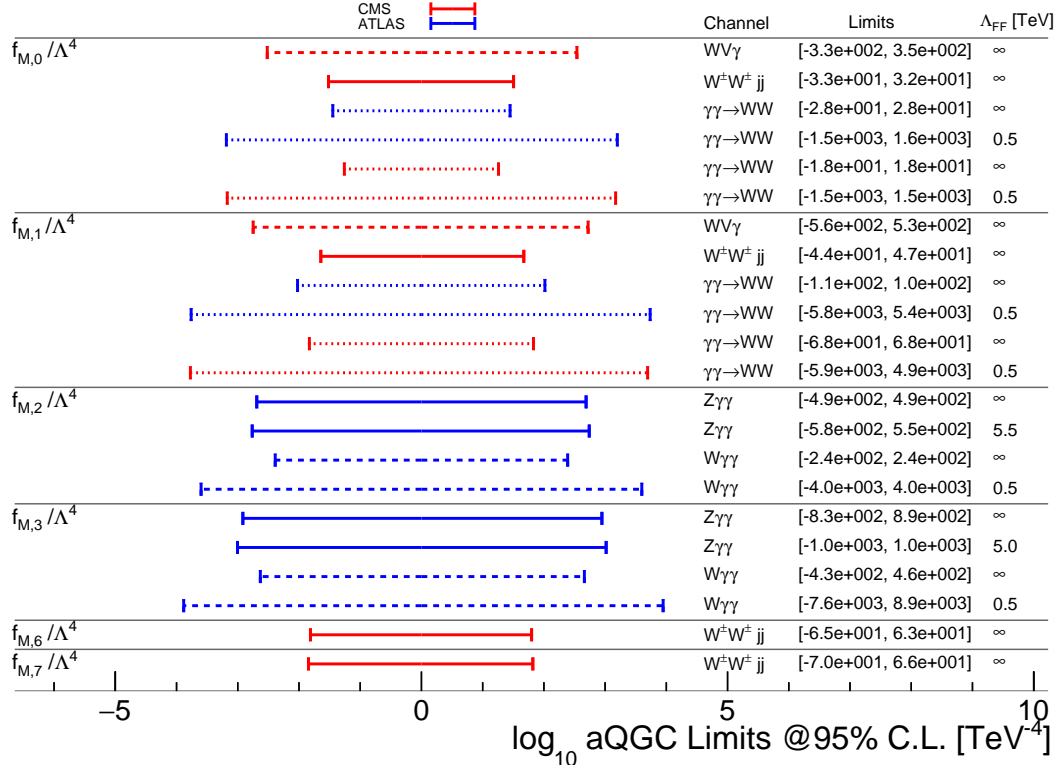


FIG. 43 Comparison of the most competitive limits involving $f_{M,i}$ coefficients, set by the LHC analyses presented in this review. All limits are based on the full 8 TeV, $\approx 20 \text{ fb}^{-1}$ data sets, except for the $\gamma\gamma \rightarrow WW$ analysis by CMS, using in addition the full $\approx 5 \text{ fb}^{-1}$ of the 7 TeV data set.

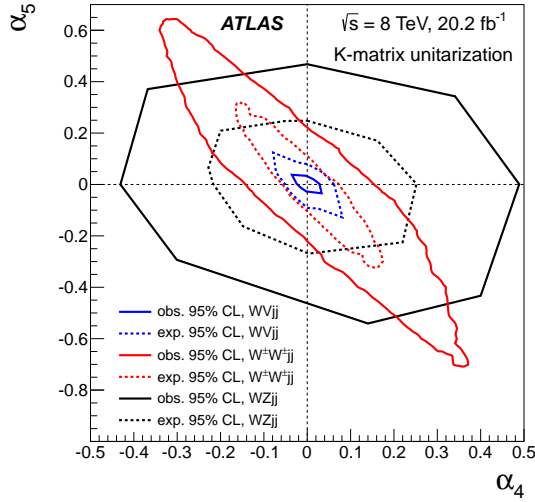


FIG. 44 Expected and observed 95% C.L. contours for aQGC limits in the α_4 , α_5 plane derived from 8 TeV $W^\pm V jj$, $W^\pm W^\pm jj$ and $W^\pm Z jj$ results by ATLAS (Aaboud *et al.*, 2016g).

measurements of carefully chosen observables that can be studied with high precision and exhibit small theoretical uncertainties. Ratios of diboson production rates have been proposed (Frye *et al.*, 2016) that could enable precision tests of the theoretical predictions, potentially to the level of being sensitive to electroweak corrections.

XI. CONCLUSIONS

The LHC has enabled studies of multi-boson interactions at an unprecedented level. Previously unobserved SM processes including vector boson fusion, triboson production and vector boson scattering were established or at least observed with first evidence. In particular, processes involving quartic gauge boson couplings were probed for the first time, allowing the test of uncharted territory in the SM.

The data taken at the LHC through 2012 have yielded many limits on aTGCs and aQGCs which have confirmed the SM gauge couplings at the level of accuracy which was accessible given the integrated luminosity and the LHC energy. The limits for aTGCs arise largely from inclusive diboson production properties at high diboson mass. The aQGC limits are determined from the inclusive production of three bosons and from the exclusive VBS production of boson pairs, also at high tri-/diboson mass. These limits are presently the most stringent, exceeding those found at LEP and the Tevatron both in the numerical limits themselves and in the breadth of the processes explored in the search for anomalous behavior.

The LHC has run at enhanced energy going from 8 TeV in 2012 to 13 TeV in 2015 and 2016. The luminosity has also risen substantially. Thus, the limits given in

this review will be improved upon in the near future. In the more distant future the high luminosity LHC will yet again very substantially improve on the aTGC and aQGC limits. These data will serve to explore the mutual couplings of the gauge bosons and ascertain if the SM is the correct description of those non-Abelian couplings.

XII. ACKNOWLEDGMENTS

The LHC experiments have already gone well beyond previous limits on triple gauge couplings and have advanced into limits on quartic gauge couplings by using the new energy frontier opened up by the LHC.

We congratulate the LHC Accelerator team for making this fantastic machine a reality and for operating it so well. Indeed, the team has more recently provided 13 TeV operation at enhanced luminosity, with more advances expected in the near future.

In addition, we thank the ATLAS and CMS electroweak and standard model working group members, past and present, for their help and cooperation in advising and encouraging us and for providing experimental details of the results quoted in this review. We also gratefully acknowledge the tremendous effort and progress on the theoretical side, enabling the predictions and MC tools utilized in the measurements presented in this review and those forthcoming.

Finally we would like to thank Matt Herndon and Harikrishnan Ramani for useful comments on the draft. The work of M.-A.P. is supported by DOE Contract No. de-sc0012704. The work of P.M. was supported in part by NSF CAREER Award NSF-PHY-1056833 and NSF-PHY-1620628.

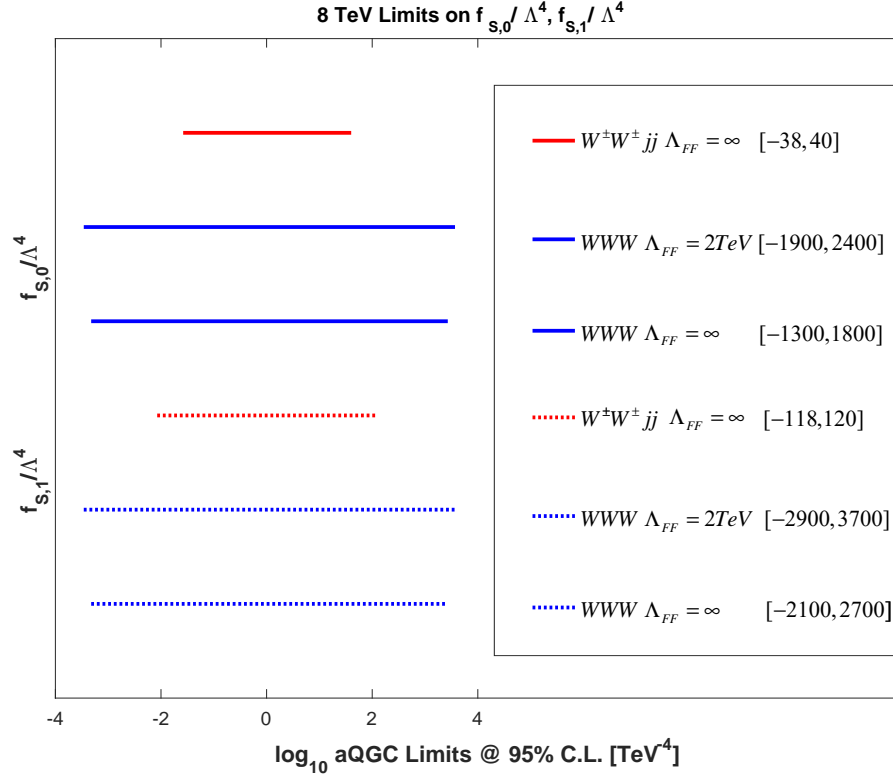


FIG. 45 Comparison of the available limits involving $f_{S,i}$ coefficients, set by the LHC analyses presented in this review. All limits are based on the full 8 TeV, $\approx 20 \text{ fb}^{-1}$ data sets.

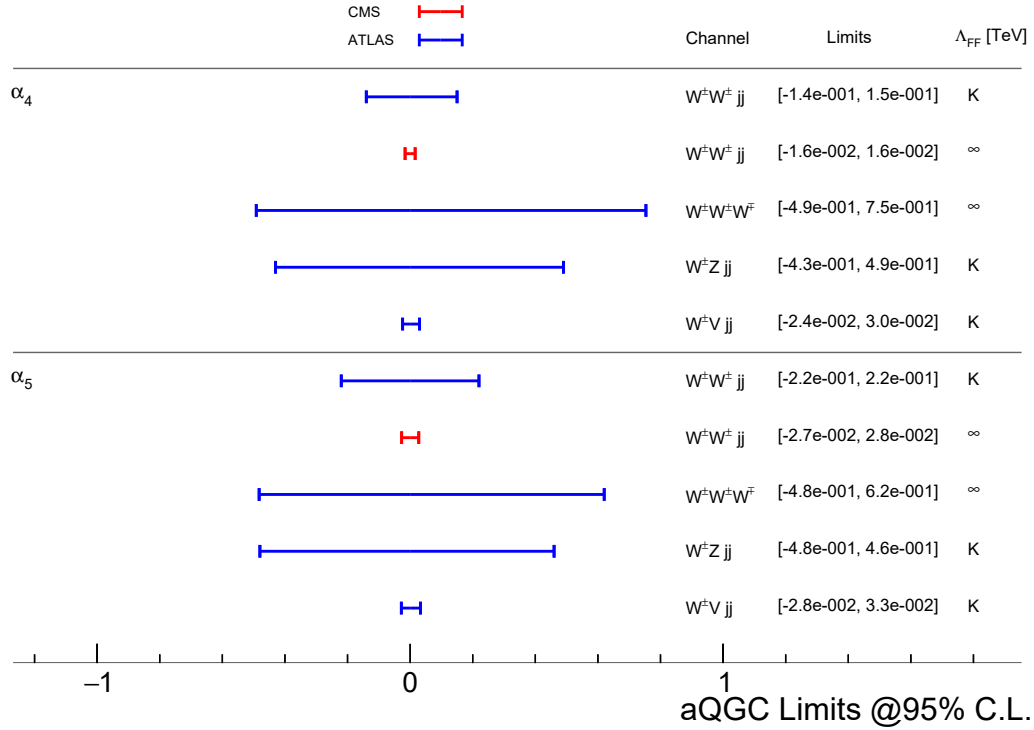
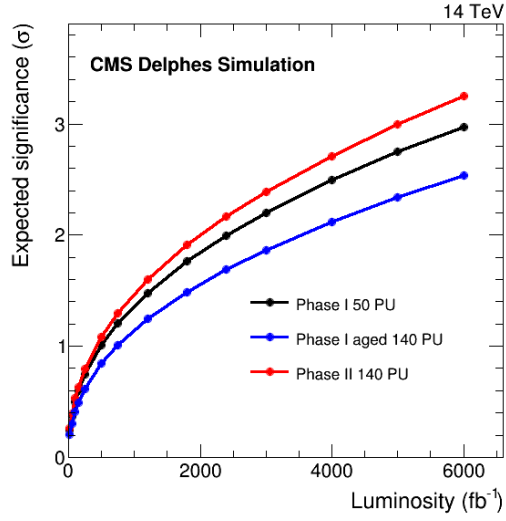
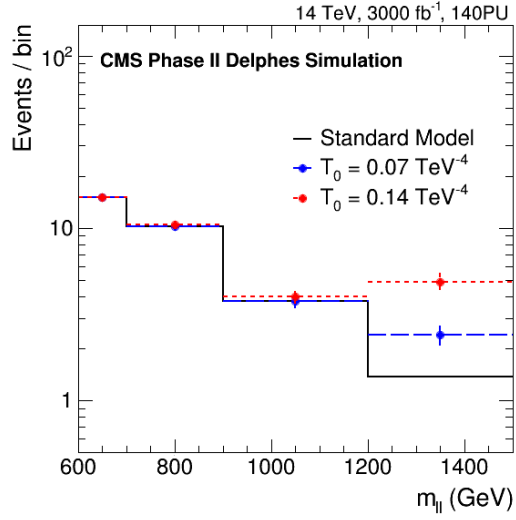


FIG. 46 Comparison of the available limits involving $\alpha_{4,5}$ coefficients, set by the LHC analyses presented in this review. All limits are based on the full 8 TeV, $\approx 20 \text{ fb}^{-1}$ data sets. A “K” in the Λ_{FF} column indicates that K-matrix unitarization was applied.



(a)



(b)

FIG. 47 Expected CMS performance for $W^\pm W^\pm$ VBS measurements at the HL-LHC (Khachatryan *et al.*, 2015j): (a) significance of measuring the longitudinal $W^\pm W^\pm$ VBS cross section as a function of integrated luminosity and (b) dilepton mass distribution, where the effect of aQGCs on the spectrum is also shown.

REFERENCES

- (2013), “Projected Performance of an Upgraded CMS Detector at the LHC and HL-LHC: Contribution to the Snowmass Process,” in *Proceedings, Community Summer Study 2013: Snowmass on the Mississippi (CSS2013): Minneapolis, MN, USA, July 29-August 6, 2013*, arXiv:1307.7135.
- Aaboud, Morad, *et al.* (2016a), “Measurement of exclusive $\gamma\gamma \rightarrow W^+W^-$ production and search for exclusive Higgs boson production in pp collisions at $\sqrt{s} = 8$ TeV using the ATLAS detector,” arXiv:1607.03745 [hep-ex].
- Aaboud, Morad, *et al.* (2016b), “Measurement of the photon identification efficiencies with the ATLAS detector using LHC Run-1 data,” arXiv:1606.01813 [hep-ex].
- Aaboud, Morad, *et al.* (2016c), “Measurement of the $W^\pm Z$ boson pair-production cross section in pp collisions at $\sqrt{s} = 13$ TeV with the ATLAS Detector,” arXiv:1606.04017 [hep-ex].
- Aaboud, Morad, *et al.* (2016d), “Measurement of the ZZ production cross section in proton-proton collisions at $\sqrt{s} = 8$ TeV using the $ZZ \rightarrow \ell^-\ell'^-\ell'^+\ell'^+$ and $ZZ \rightarrow \ell^-\ell'^+\nu\bar{\nu}$ decay channels with the ATLAS detector,” .
- Aaboud, Morad, *et al.* (2016e), “Measurement of $W^\pm W^\pm$ Vector Boson Scattering and Limits on Anomalous Quartic Gauge Couplings with the ATLAS Detector,” .
- Aaboud, Morad, *et al.* (2016f), “Measurement of W^+W^- production in association with one jet in proton-proton collisions at $\sqrt{s} = 8$ TeV with the ATLAS detector,” arXiv:1608.03086 [hep-ex].
- Aaboud, Morad, *et al.* (2016g), “Search for anomalous electroweak production of WW/WZ in association with a high-mass dijet system in pp collisions at $\sqrt{s} = 8$ TeV with the ATLAS detector,” arXiv:1609.05122 [hep-ex].
- Aaboud, Morad, *et al.* (2016h), “Search for triboson $W^\pm W^\pm W^\mp$ production in pp collisions at $\sqrt{s} = 8$ TeV with the ATLAS detector,” arXiv:1610.05088 [hep-ex].
- Aad, G, *et al.* (2008), “The ATLAS Experiment at the CERN Large Hadron Collider,” JINST **3**, S08003.
- Aad, G, *et al.* (2016a), “Combination of results from the ATLAS and CMS experiments on anomalous triple gauge couplings in ZZ production from pp collisions at a centre-of-mass energy of 7 TeV at the LHC,” .
- Aad, Georges, *et al.* (2011a), “Measurement of the W^+W^- cross section in $\sqrt{s} = 7$ TeV pp collisions with ATLAS,” Phys.Rev.Lett. **107**, 041802, arXiv:1104.5225.
- Aad, Georges, *et al.* (2011b), “Measurement of $W\gamma$ and $Z\gamma$ production in proton-proton collisions at $\sqrt{s} = 7$ TeV with the ATLAS Detector,” JHEP **1109**, 072, arXiv:1106.1592.
- Aad, Georges, *et al.* (2012a), “Measurement of the inclusive W^\pm and Z/γ cross sections in the electron and muon decay channels in pp collisions at $\sqrt{s} = 7$ TeV with the ATLAS detector,” Phys. Rev. **D85**, 072004, arXiv:1109.5141 [hep-ex].
- Aad, Georges, *et al.* (2012b), “Measurement of the isolated di-photon cross-section in pp collisions at $\sqrt{s} = 7$ TeV with the ATLAS detector,” Phys. Rev. **D85**, 012003, arXiv:1107.0581 [hep-ex].
- Aad, Georges, *et al.* (2012c), “Measurement of the total ZZ production cross section in the four-lepton channel using 5.8 fb^{-1} of ATLAS data at $\sqrt{s} = 8$ TeV,” .
- Aad, Georges, *et al.* (2012d), “Measurement of the WW cross section in $\sqrt{s} = 7$ TeV pp collisions with the ATLAS detector and limits on anomalous gauge couplings,” Phys.Lett. **B712**, 289–308, arXiv:1203.6232.
- Aad, Georges, *et al.* (2012e), “Measurement of the WZ Production Cross Section and Limits on Anomalous Triple Gauge Couplings in Proton-Proton Collisions at $\sqrt{s} = 7$ TeV with the ATLAS Detector,” Phys.Lett. **B709**, 341–357, arXiv:1111.5570.
- Aad, Georges, *et al.* (2012f), “Measurement of the ZZ production cross section and limits on anomalous neutral triple gauge couplings in proton-proton collisions at $\sqrt{s} = 7$ TeV with the ATLAS detector,” Phys.Rev.Lett. **108**, 041804, arXiv:1110.5016.
- Aad, Georges, *et al.* (2012g), “Measurement of $W\gamma$ and $Z\gamma$ production cross sections in pp collisions at $\sqrt{s} = 7$ TeV and limits on anomalous triple gauge couplings with the ATLAS detector,” Phys.Lett. **B717**, 49–69, arXiv:1205.2531.
- Aad, Georges, *et al.* (2012h), “Measurement of $W^\pm Z$ Production in Proton-Proton Collisions at $\sqrt{s} = 7$ TeV with the ATLAS Detector,” Eur.Phys.J. **C72**, 2173, arXiv:1208.1390.
- Aad, Georges, *et al.* (2012i), “Observation of a new particle in the search for the Standard Model Higgs boson with the ATLAS detector at the LHC,” Phys. Lett. **B716**, 1–29, arXiv:1207.7214 [hep-ex].
- Aad, Georges, *et al.* (2012j), “Performance of Missing Transverse Momentum Reconstruction in Proton-Proton Collisions at 7 TeV with ATLAS,” Eur. Phys. J. **C72**, 1844, arXiv:1108.5602 [hep-ex].
- Aad, Georges, *et al.* (2012k), “Performance of the ATLAS Trigger System in 2010,” Eur. Phys. J. **C72**, 1849, arXiv:1110.1530 [hep-ex].
- Aad, Georges, *et al.* (2012l), “Search for supersymmetry in final states with jets, missing transverse momentum and one isolated lepton in $\sqrt{s} = 7$ TeV pp collisions using 1 fb^{-1} of ATLAS data,” Phys. Rev. **D85** (1), 012006, [Erratum: Phys. Rev.D87,099903(2013)], arXiv:1109.6606 [hep-ex].
- Aad, Georges, *et al.* (2012m), *Studies of Vector Boson Scattering with an Upgraded ATLAS Detector at a High-Luminosity LHC*, Tech. Rep. ATL-PHYS-PUB-2012-005 (CERN, Geneva).
- Aad, Georges, *et al.* (2013a), “Jet energy measurement with the ATLAS detector in proton-proton collisions at $\sqrt{s} = 7$ TeV,” Eur. Phys. J. **C73** (3), 2304, arXiv:1112.6426 [hep-ex].
- Aad, Georges, *et al.* (2013b), “Jet energy resolution in proton-proton collisions at $\sqrt{s} = 7$ TeV recorded in 2010 with the ATLAS detector,” Eur. Phys. J. **C73** (3), 2306, arXiv:1210.6210 [hep-ex].
- Aad, Georges, *et al.* (2013c), “Measurement of isolated-photon pair production in pp collisions at $\sqrt{s} = 7$ TeV with the ATLAS detector,” JHEP **01**, 086, arXiv:1211.1913 [hep-ex].
- Aad, Georges, *et al.* (2013d), “Measurement of W^+W^- production in pp collisions at $\sqrt{s} = 7$ TeV with the ATLAS detector and limits on anomalous WWZ and $WW\gamma$ couplings,” Phys.Rev. **D87** (11), 112001, arXiv:1210.2979.
- Aad, Georges, *et al.* (2013e), “Measurement of ZZ production in pp collisions at $\sqrt{s} = 7$ TeV and limits on anomalous ZZZ and $ZZ\gamma$ couplings with the ATLAS detector,” JHEP **1303**, 128, arXiv:1211.6096.
- Aad, Georges, *et al.* (2013f), “Measurements of $W\gamma$ and $Z\gamma$ production in pp collisions at $\sqrt{s} = 7$ TeV with the ATLAS detector at the LHC,” Phys.Rev. **D87** (11), 112003, [Erratum: Phys. Rev.D91, no.11, 119901 (2015)], arXiv:1302.1283.

- Aad, Georges, *et al.* (2013g), “Physics at a High-Luminosity LHC with ATLAS,” in *Community Summer Study 2013: Snowmass on the Mississippi (CSS2013) Minneapolis, MN, USA, July 29-August 6, 2013*, arXiv:1307.7292 [hep-ex].
- Aad, Georges, *et al.* (2013h), *Studies of Vector Boson Scattering And Triboson Production with an Upgraded ATLAS Detector at a High-Luminosity LHC*, Tech. Rep. ATL-PHYS-PUB-2013-006 (CERN, Geneva).
- Aad, Georges, *et al.* (2014a), “Electron and photon energy calibration with the ATLAS detector using LHC Run 1 data,” *Eur. Phys. J.* **C74** (10), 3071, arXiv:1407.5063 [hep-ex].
- Aad, Georges, *et al.* (2014b), “Electron reconstruction and identification efficiency measurements with the ATLAS detector using the 2011 LHC proton-proton collision data,” *Eur. Phys. J.* **C74** (7), 2941, arXiv:1404.2240 [hep-ex].
- Aad, Georges, *et al.* (2014c), “Evidence for Electroweak Production of $W^\pm W^\pm jj$ in pp Collisions at $\sqrt{s} = 8$ TeV with the ATLAS Detector,” *Phys. Rev. Lett.* **113**, 141803, arXiv:1405.6241.
- Aad, Georges, *et al.* (2014d), “Measurement of the electroweak production of dijets in association with a Z -boson and distributions sensitive to vector boson fusion in proton-proton collisions at $\sqrt{s} = 8$ TeV using the ATLAS detector,” *JHEP* **1404**, 031, arXiv:1401.7610.
- Aad, Georges, *et al.* (2014e), “Measurement of the muon reconstruction performance of the ATLAS detector using 2011 and 2012 LHC proton proton collision data,” *Eur. Phys. J.* **C74** (11), 3130, arXiv:1407.3935 [hep-ex].
- Aad, Georges, *et al.* (2014f), “Muon reconstruction efficiency and momentum resolution of the ATLAS experiment in proton-proton collisions at $\sqrt{s} = 7$ TeV in 2010,” *Eur. Phys. J.* **C74** (9), 3034, arXiv:1404.4562 [hep-ex].
- Aad, Georges, *et al.* (2015a), *ATLAS Phase-II Upgrade Scoping Document*, Tech. Rep. CERN-LHCC-2015-020. LHCC-G-166 (CERN, Geneva).
- Aad, Georges, *et al.* (2015b), “Evidence of $W\gamma\gamma$ Production in pp Collisions at $\sqrt{s} = 8$ TeV and Limits on Anomalous Quartic Gauge Couplings with the ATLAS Detector,” *Phys. Rev. Lett.* **115** (3), 031802, arXiv:1503.03243 [hep-ex].
- Aad, Georges, *et al.* (2015c), “Jet energy measurement and its systematic uncertainty in proton-proton collisions at $\sqrt{s} = 7$ TeV with the ATLAS detector,” *Eur. Phys. J.* **C75**, 17, arXiv:1406.0076 [hep-ex].
- Aad, Georges, *et al.* (2015d), “Measurement of the $WW+WZ$ cross section and limits on anomalous triple gauge couplings using final states with one lepton, missing transverse momentum, and two jets with the ATLAS detector at $\sqrt{s} = 7$ TeV,” *JHEP* **01**, 049, arXiv:1410.7238 [hep-ex].
- Aad, Georges, *et al.* (2015e), “Performance of the ATLAS muon trigger in pp collisions at $\sqrt{s} = 8$ TeV,” *Eur. Phys. J.* **C75**, 120, arXiv:1408.3179 [hep-ex].
- Aad, Georges, *et al.* (2016b), “Combination of searches for WW , WZ , and ZZ resonances in pp collisions at $\sqrt{s} = 8$ TeV with the ATLAS detector,” *Phys. Lett.* **B755**, 285–305, arXiv:1512.05099 [hep-ex].
- Aad, Georges, *et al.* (2016c), “Constraints on non-Standard Model Higgs boson interactions in an effective Lagrangian using differential cross sections measured in the $H \rightarrow \gamma\gamma$ decay channel at $\sqrt{s} = 8$ TeV with the ATLAS detector,” *Phys. Lett.* **B753**, 69–85, arXiv:1508.02507 [hep-ex].
- Aad, Georges, *et al.* (2016d), “Identification of boosted, hadronically decaying W bosons and comparisons with ATLAS data taken at $\sqrt{s} = 8$ TeV,” *Eur. Phys. J.* **C76** (3), 154, arXiv:1510.05821 [hep-ex].
- Aad, Georges, *et al.* (2016e), “Measurement of total and differential W^+W^- production cross sections in proton-proton collisions at $\sqrt{s} = 8$ TeV with the ATLAS detector and limits on anomalous triple-gauge-boson couplings,” arXiv:1603.01702 [hep-ex].
- Aad, Georges, *et al.* (2016f), “Measurements of $W^\pm Z$ production cross sections in pp collisions at $\sqrt{s} = 8$ TeV with the ATLAS detector and limits on anomalous gauge boson self-couplings,” arXiv:1603.02151 [hep-ex].
- Aad, Georges, *et al.* (2016g), “Measurements of $Z\gamma$ and $Z\gamma\gamma$ production in pp collisions at $\sqrt{s} = 8$ TeV with the ATLAS detector,” arXiv:1604.05232 [hep-ex].
- Aad, Georges, *et al.* (2016h), “Performance of algorithms that reconstruct missing transverse momentum in $\sqrt{s} = 8$ TeV proton-proton collisions in the ATLAS detector,” arXiv:1609.09324 [hep-ex].
- Aaltonen, T, *et al.* (2011), “Limits on Anomalous Trilinear Gauge Couplings in $Z\gamma$ Events from $p\bar{p}$ Collisions at $\sqrt{s} = 1.96$ TeV,” *Phys. Rev. Lett.* **107**, 051802, arXiv:1103.2990 [hep-ex].
- Abazov, V M, *et al.* (2008), “Search for ZZ and $Z\gamma^*$ production in $p\bar{p}$ collisions at $\sqrt{s} = 1.96$ TeV and limits on anomalous ZZZ and $ZZ\gamma^*$ couplings,” *Phys. Rev. Lett.* **100**, 131801, arXiv:0712.0599 [hep-ex].
- Abazov, Victor Mukhamedovich, *et al.* (2012), “Limits on anomalous trilinear gauge boson couplings from WW , WZ and $W\gamma$ production in $p\bar{p}$ collisions at $\sqrt{s} = 1.96$ TeV,” *Phys. Lett.* **B718**, 451–459, arXiv:1208.5458 [hep-ex].
- Abazov, Victor Mukhamedovich, *et al.* (2013), “Search for anomalous quartic $WW\gamma\gamma$ couplings in dielectron and missing energy final states in $p\bar{p}$ collisions at $\sqrt{s} = 1.96$ TeV,” *Phys. Rev.* **D88**, 012005, arXiv:1305.1258 [hep-ex].
- Abbiendi, G, *et al.* (2004), “Constraints on anomalous quartic gauge boson couplings from ν anti- ν gamma gamma and q anti- q gamma gamma events at LEP-2,” *Phys. Rev.* **D70**, 032005, arXiv:hep-ex/0402021 [hep-ex].
- Achard, P, *et al.* (2002), “Study of the $W^+W^-\gamma$ process and limits on anomalous quartic gauge boson couplings at LEP,” *Phys. Lett.* **B527**, 29–38, arXiv:hep-ex/0111029 [hep-ex].
- Adam, W, *et al.* (2006), “The CMS high level trigger,” *Eur. Phys. J.* **C46**, 605–667, arXiv:hep-ex/0512077 [hep-ex].
- Aihara, H, *et al.* (1995), “Anomalous gauge boson interactions,” arXiv:hep-ph/9503425 [hep-ph].
- Alboreanu, Ana, Wolfgang Kilian, and Juergen Reuter (2008), “Resonances and Unitarity in Weak Boson Scattering at the LHC,” *JHEP* **11**, 010, arXiv:0806.4145 [hep-ph].
- Aleksan, R, *et al.* (2013), “Physics Briefing Book: Input for the Strategy Group to draft the update of the European Strategy for Particle Physics,” .
- Alioli, Simone, Christian W. Bauer, Calvin Berggren, Frank J. Tackmann, Jonathan R. Walsh, and Saba Zuberi (2014), “Matching Fully Differential NNLO Calculations and Parton Showers,” *JHEP* **06**, 089, arXiv:1311.0286 [hep-ph].
- Alioli, Simone, Fabrizio Caola, Gionata Luisoni, and Raul Rntsch (2016), “ ZZ production in gluon fusion at NLO matched to parton-shower,” arXiv:1609.09719 [hep-ph].
- Alioli, Simone, Paolo Nason, Carlo Oleari, and Emanuele Re (2010), “A general framework for implementing NLO calculations in shower Monte Carlo programs: the POWHEG BOX,” *JHEP* **06**, 043, arXiv:1002.2581 [hep-ph].

- Altarelli, G, T. Sjostrand, and F. Zwirner, Eds. (1996), *Physics at LEP2: Vol. 1*.
- Alwall, J, R. Frederix, S. Frixione, V. Hirschi, F. Maltoni, *et al.* (2014), “The automated computation of tree-level and next-to-leading order differential cross sections, and their matching to parton shower simulations,” *JHEP* **07**, 079, arXiv:1405.0301 [hep-ph].
- Andersen, J R, *et al.* (2013), “Handbook of LHC Higgs Cross Sections: 3. Higgs Properties,” 10.5170/CERN-2013-004, arXiv:1307.1347 [hep-ph].
- Andersen, J R, *et al.* (2016), “Les Houches 2015: Physics at TeV Colliders Standard Model Working Group Report,” in *9th Les Houches Workshop on Physics at TeV Colliders (PhysTeV 2015) Les Houches, France, June 1-19, 2015*, arXiv:1605.04692 [hep-ph].
- Appelquist, Thomas, and Claude W. Bernard (1980), “Strongly Interacting Higgs Bosons,” *Phys. Rev.* **D22**, 200.
- Appelquist, Thomas, and Guo-Hong Wu (1993), “The Electroweak chiral Lagrangian and new precision measurements,” *Phys. Rev.* **D48**, 3235–3241, arXiv:hep-ph/9304240 [hep-ph].
- Arkani-Hamed, N, A. G. Cohen, E. Katz, and A. E. Nelson (2002), “The Littlest Higgs,” *JHEP* **07**, 034, arXiv:hep-ph/0206021 [hep-ph].
- Arkani-Hamed, Nima, Andrew G. Cohen, and Howard Georgi (2001), “Electroweak symmetry breaking from dimensional deconstruction,” *Phys. Lett.* **B513**, 232–240, arXiv:hep-ph/0105239 [hep-ph].
- Arnold, K, *et al.* (2009), “VBFNLO: A Parton level Monte Carlo for processes with electroweak bosons,” *Comput. Phys. Commun.* **180**, 1661–1670, arXiv:0811.4559 [hep-ph].
- Arnold, K, *et al.* (2011), “VBFNLO: A Parton Level Monte Carlo for Processes with Electroweak Bosons – Manual for Version 2.5.0,” arXiv:1107.4038 [hep-ph].
- ATLAS Collaboration, (2011), “Expected photon performance in the ATLAS experiment,” ATL-PHYS-PUB-2011-007.
- ATLAS Collaboration, (2012a), “Measurements of the photon identification efficiency with the ATLAS detector using 4.9 fb⁻¹ of *pp* collision data collected in 2011,” ATLAS-CONF-2012-123.
- ATLAS Collaboration, (2012b), “Performance of the ATLAS Electron and Photon Trigger in *pp* Collisions at $\sqrt{s} = 7$ TeV in 2011,” ATLAS-CONF-2012-048.
- ATLAS Collaboration, (2013), “Performance of Missing Transverse Momentum Reconstruction in ATLAS studied in Proton–Proton Collisions recorded in 2012 at $\sqrt{s} = 8$ TeV,” ATLAS-CONF-2013-082.
- ATLAS Collaboration, (2014a), “Electron efficiency measurements with the ATLAS detector using the 2012 LHC proton–proton collision data,” ATLAS-CONF-2014-032.
- ATLAS Collaboration, (2014b), “Pile-up Correction in Missing Transverse Momentum Reconstruction in the ATLAS Experiment in Proton–Proton Collisions at $\sqrt{s} = 8$ TeV,” ATLAS-CONF-2014-019.
- ATLAS Collaboration, (2015), “Monte Carlo Calibration and Combination of In-situ Measurements of Jet Energy Scale, Jet Energy Resolution and Jet Mass in ATLAS,” ATLAS-CONF-2015-037.
- Baak, M, *et al.* (2013), “Working Group Report: Precision Study of Electroweak Interactions,” in *Community Summer Study 2013: Snowmass on the Mississippi (CSS2013) Minneapolis, MN, USA, July 29-August 6, 2013*, arXiv:1310.6708 [hep-ph].
- Baglio, J, *et al.* (2014), “Release Note - VBFNLO 2.7.0,” arXiv:1404.3940 [hep-ph].
- Bardeen, M, *et al.* (2013), “Proceedings, Community Summer Study 2013: Snowmass on the Mississippi (CSS2013),”.
- Baur, U, and Edmond L. Berger (1993), “Probing the weak boson sector in $Z\gamma$ production at hadron colliders,” *Phys. Rev.* **D47**, 4889–4904.
- Baur, U, Tao Han, N. Kauer, R. Sobey, and D. Zeppenfeld (1997), “ $W\gamma\gamma$ production at the Fermilab Tevatron collider: Gauge invariance and radiation amplitude zero,” *Phys. Rev.* **D56**, 140–150, arXiv:hep-ph/9702364 [hep-ph].
- Baur, U, and D. Zeppenfeld (1993), “Measuring three vector boson couplings in $qq \rightarrow qqW$ at the SSC,” in *Workshop on Physics at Current Accelerators and the Supercollider Argonne, Illinois, June 2-5, 1993*, arXiv:hep-ph/9309227 [hep-ph].
- Beaudette, Florian (2013), “The CMS Particle Flow Algorithm,” in *Proceedings, International Conference on Calorimetry for the High Energy Frontier (CHEF 2013)*, pp. 295–304, arXiv:1401.8155 [hep-ex].
- Belanger, G, and F. Boudjema (1992), “ $\gamma\gamma \rightarrow W^+W^-$ and $\gamma\gamma \rightarrow ZZ$ as tests of novel quartic couplings,” *Phys. Lett.* **B288**, 210–220.
- Belanger, G, F. Boudjema, Y. Kurihara, D. Perret-Gallix, and A. Semenov (2000), “Bosonic quartic couplings at LEP-2,” *Eur. Phys. J.* **C13**, 283–293, arXiv:hep-ph/9908254 [hep-ph].
- Biedermann, B, A. Denner, S. Dittmaier, L. Hofer, and B. Jger (2016a), “Electroweak corrections to $pp \rightarrow \mu^+\mu^-e^+e^- + X$ at the LHC: a Higgs background study,” *Phys. Rev. Lett.* **116** (16), 161803, arXiv:1601.07787 [hep-ph].
- Biedermann, Benedikt, Marina Billoni, Ansgar Denner, Stefan Dittmaier, Lars Hofer, Barbara Jäger, and Lukas Salfelder (2016b), “Next-to-leading-order electroweak corrections to $pp \rightarrow W^+W^- \rightarrow 4$ leptons at the LHC,” *JHEP* **06**, 065, arXiv:1605.03419 [hep-ph].
- Boughezal, Radja, John M. Campbell, R. Keith Ellis, Christfried Focke, Walter Giele, Xiaohui Liu, Frank Petriello, and Ciaran Williams (2016), “Color Singlet Production at NNLO in MCFM,” Submitted to: *JHEP* arXiv:1605.08011 [hep-ph].
- Buchmuller, W, and D. Wyler (1986), “Effective Lagrangian Analysis of New Interactions and Flavor Conservation,” *Nucl. Phys.* **B268**, 621–653.
- Buttar, C, *et al.* (2006), “Les houches physics at TeV colliders 2005, standard model and Higgs working group: Summary report,” in *Physics at TeV colliders. Proceedings, Workshop, Les Houches, France, May 2-20, 2005*, arXiv:hep-ph/0604120 [hep-ph].
- Butter, Anja, Oscar J. P. Éboli, J. Gonzalez-Fraile, M. C. Gonzalez-Garcia, Tilman Plehn, and Michael Rauch (2016), “The Gauge-Higgs Legacy of the LHC Run I,” *JHEP* **07**, 152, arXiv:1604.03105 [hep-ph].
- Campanario, F, M. Kerner, L. D. Ninh, M. Rauch, R. Roth, and D. Zeppenfeld (2015), “NLO corrections to processes with electroweak bosons at hadron colliders,” *Proceedings, Advances in Computational Particle Physics: Final Meeting (SFB-TR-9)*, *Nucl. Part. Phys. Proc.* **261-262**, 268–307.
- Campbell, John M, and R. Keith Ellis (1999), “An Update on vector boson pair production at hadron colliders,” *Phys. Rev.* **D60**, 113006, arXiv:hep-ph/9905386 [hep-ph].

- Campbell, John M, R. Keith Ellis, and Walter T. Giele (2015), “A Multi-Threaded Version of MCFM,” *Eur. Phys. J.* **C75** (6), 246, arXiv:1503.06182 [physics.comp-ph].
- Campbell, John M, R. Keith Ellis, Ye Li, and Ciaran Williams (2016), “Predictions for diphoton production at the LHC through NNLO in QCD,” *JHEP* **07**, 148, arXiv:1603.02663 [hep-ph].
- Campbell, John M, R. Keith Ellis, and Ciaran Williams (2011a), “Gluon-Gluon Contributions to W^+W^- Production and Higgs Interference Effects,” *JHEP* **10**, 005, arXiv:1107.5569 [hep-ph].
- Campbell, John M, R. Keith Ellis, and Ciaran Williams (2011b), “Vector boson pair production at the LHC,” *JHEP* **07**, 018, arXiv:1105.0020 [hep-ph].
- Caola, Fabrizio, Kirill Melnikov, Raoul Rntsch, and Lorenzo Tancredi (2015), “QCD corrections to ZZ production in gluon fusion at the LHC,” *Phys. Rev.* **D92** (9), 094028, arXiv:1509.06734 [hep-ph].
- Caola, Fabrizio, Kirill Melnikov, Raoul Rntsch, and Lorenzo Tancredi (2016), “QCD corrections to W^+W^- production through gluon fusion,” *Phys. Lett.* **B754**, 275–280, arXiv:1511.08617 [hep-ph].
- Cascioli, F, T. Gehrmann, M. Grazzini, S. Kallweit, P. Maierhfer, A. von Manteuffel, S. Pozzorini, D. Rathlev, L. Tancredi, and E. Weihs (2014), “ZZ production at hadron colliders in NNLO QCD,” *Phys. Lett.* **B735**, 311–313, arXiv:1405.2219 [hep-ph].
- Chanowitz, Michael S, and Mary K. Gaillard (1985), “The TeV Physics of Strongly Interacting W’s and Z’s,” *Nucl. Phys.* **B261**, 379–431.
- Chatrchyan, S, *et al.* (2008), “The CMS experiment at the CERN LHC,” *JINST* **3**, S08004.
- Chatrchyan, S, *et al.* (2010), “Performance of the CMS Level-1 Trigger during Commissioning with Cosmic Ray Muons,” *JINST* **5**, T03002, arXiv:0911.5422 [physics.ins-det].
- Chatrchyan, Serguei, *et al.* (2011a), “Determination of Jet Energy Calibration and Transverse Momentum Resolution in CMS,” *JINST* **6**, P11002, arXiv:1107.4277 [physics.ins-det].
- Chatrchyan, Serguei, *et al.* (2011b), “Measurement of W^+W^- production and search for the Higgs boson in pp collisions at $\sqrt{s} = 7$ TeV,” *Phys. Lett.* **B699**, 25–47, arXiv:1102.5429 [hep-ex].
- Chatrchyan, Serguei, *et al.* (2011c), “Measurement of $W\gamma$ and $Z\gamma$ production in pp collisions at $\sqrt{s} = 7$ TeV,” *Phys. Lett.* **B701**, 535–555, arXiv:1105.2758 [hep-ex].
- Chatrchyan, Serguei, *et al.* (2012a), “Measurement of the Production Cross Section for Pairs of Isolated Photons in pp collisions at $\sqrt{s} = 7$ TeV,” *JHEP* **01**, 133, arXiv:1110.6461 [hep-ex].
- Chatrchyan, Serguei, *et al.* (2012b), “Observation of a new boson at a mass of 125 GeV with the CMS experiment at the LHC,” *Phys. Lett.* **B716**, 30–61, arXiv:1207.7235 [hep-ex].
- Chatrchyan, Serguei, *et al.* (2013a), “Measurement of the hadronic activity in events with a Z and two jets and extraction of the cross section for the electroweak production of a Z with two jets in pp collisions at $\sqrt{s} = 7$ TeV,” *JHEP* **10**, 062, arXiv:1305.7389 [hep-ex].
- Chatrchyan, Serguei, *et al.* (2013b), “Measurement of the production cross section for $Z\gamma \rightarrow \nu\bar{\nu}\gamma$ in pp collisions at $\sqrt{s} = 7$ TeV and limits on $ZZ\gamma$ and $Z\gamma\gamma$ triple gauge boson couplings,” *JHEP* **10**, 164, arXiv:1309.1117 [hep-ex].
- Chatrchyan, Serguei, *et al.* (2013c), “Measurement of the sum of WW and WZ production with W +dijet events in pp collisions at $\sqrt{s} = 7$ TeV,” *Eur. Phys. J.* **C73** (2), 2283, arXiv:1210.7544 [hep-ex].
- Chatrchyan, Serguei, *et al.* (2013d), “Measurement of the W^+W^- Cross section in pp Collisions at $\sqrt{s} = 7$ TeV and Limits on Anomalous $WW\gamma$ and WWZ couplings,” *Eur. Phys. J.* **C73** (10), 2610, arXiv:1306.1126 [hep-ex].
- Chatrchyan, Serguei, *et al.* (2013e), “Measurement of the ZZ production cross section and search for anomalous couplings in 2 l2l’ final states in pp collisions at $\sqrt{s} = 7$ TeV,” *JHEP* **01**, 063, arXiv:1211.4890 [hep-ex].
- Chatrchyan, Serguei, *et al.* (2013f), “Measurement of W + W - and ZZ production cross sections in pp collisions at $\sqrt{s} = 8$ TeV,” *Phys. Lett.* **B721**, 190–211, arXiv:1301.4698 [hep-ex].
- Chatrchyan, Serguei, *et al.* (2013g), “Study of exclusive two-photon production of W^+W^- in pp collisions at $\sqrt{s} = 7$ TeV and constraints on anomalous quartic gauge couplings,” *JHEP* **07**, 116, arXiv:1305.5596 [hep-ex].
- Chatrchyan, Serguei, *et al.* (2013h), “The performance of the CMS muon detector in proton-proton collisions at $\sqrt{s} = 7$ TeV at the LHC,” *JINST* **8**, P11002, arXiv:1306.6905 [physics.ins-det].
- Chatrchyan, Serguei, *et al.* (2014a), “Measurement of differential cross sections for the production of a pair of isolated photons in pp collisions at $\sqrt{s} = 7$ TeV,” *Eur. Phys. J.* **C74** (11), 3129, arXiv:1405.7225 [hep-ex].
- Chatrchyan, Serguei, *et al.* (2014b), “Measurement of inclusive W and Z boson production cross sections in pp collisions at $\sqrt{s} = 8$ TeV,” *Phys. Rev. Lett.* **112**, 191802, arXiv:1402.0923 [hep-ex].
- Chatrchyan, Serguei, *et al.* (2014c), “Measurement of the $W\gamma$ and $Z\gamma$ inclusive cross sections in pp collisions at $\sqrt{s} = 7$ TeV and limits on anomalous triple gauge boson couplings,” *Phys. Rev.* **D89** (9), 092005, arXiv:1308.6832 [hep-ex].
- Chatrchyan, Serguei, *et al.* (2014d), “Measurement of WZ and ZZ production in pp collisions at $\sqrt{s} = 8$ TeV in final states with b-tagged jets,” *Eur. Phys. J.* **C74** (8), 2973, arXiv:1403.3047 [hep-ex].
- Chatrchyan, Serguei, *et al.* (2014e), “Search for $WW\gamma$ and $WZ\gamma$ production and constraints on anomalous quartic gauge couplings in pp collisions at $\sqrt{s} = 8$ TeV,” *Phys. Rev.* **D90** (3), 032008, arXiv:1404.4619 [hep-ex].
- Contino, Roberto (2016), “HOW BEST TO USE LHC RESULTS AND EFT TO PROBE PHYSICS ABOVE THE SCALE OF THE LHC,” in *SEARCH 2016, Oxford University, September*.
- Corbett, Tyler, O. J. P. Éboli, J. Gonzalez-Fraile, and M. C. Gonzalez-Garcia (2013), “Determining Triple Gauge Boson Couplings from Higgs Data,” *Phys. Rev. Lett.* **111**, 011801, arXiv:1304.1151 [hep-ph].
- Cornwall, John M, David N. Levin, and George Tiktopoulos (1973), “Uniqueness of spontaneously broken gauge theories,” *Phys. Rev. Lett.* **30**, 1268–1270, [Erratum: *Phys. Rev. Lett.* 31,572(1973)].
- Cornwall, John M, David N. Levin, and George Tiktopoulos (1974), “Derivation of Gauge Invariance from High-Energy Unitarity Bounds on the s Matrix,” *Phys. Rev.* **D10**, 1145, [Erratum: *Phys. Rev.* D11,972(1975)].
- Council, CERN (2013), “The European Strategy for Particle Physics Update 2013. 16th Session of European Strategy Council,” .
- Csaki, Csaba, Christophe Grojean, Hitoshi Murayama, Luigi

- Pilo, and John Terning (2004a), “Gauge theories on an interval: Unitarity without a Higgs,” *Phys. Rev.* **D69**, 055006, arXiv:hep-ph/0305237 [hep-ph].
- Csaki, Csaba, Christophe Grojean, Luigi Pilo, and John Terning (2004b), “Towards a realistic model of Higgsless electroweak symmetry breaking,” *Phys. Rev. Lett.* **92**, 101802, arXiv:hep-ph/0308038 [hep-ph].
- Curtin, David, Prerit Jaiswal, and Patrick Meade (2013a), “Charginos Hiding In Plain Sight,” *Phys. Rev.* **D87** (3), 031701, arXiv:1206.6888 [hep-ph].
- Curtin, David, Prerit Jaiswal, Patrick Meade, and Pin-Ju Tien (2013b), “Casting Light on BSM Physics with SM Standard Candles,” *JHEP* **08**, 068, arXiv:1304.7011 [hep-ph].
- Curtin, David, Patrick Meade, and Pin-Ju Tien (2014), “Natural SUSY in Plain Sight,” *Phys. Rev.* **D90** (11), 115012, arXiv:1406.0848 [hep-ph].
- Czakon, Michal, Alexander Mitov, Michele Papucci, Joshua T. Ruderman, and Andreas Weiler (2014), “Closing the stop gap,” *Phys. Rev. Lett.* **113** (20), 201803, arXiv:1407.1043 [hep-ph].
- Dawson, S, P. Jaiswal, Ye Li, H. Ramani, and Mao Zeng (2016), “Resummation of Jet Veto Logarithms at $N^3LL_a + NNLO$ for W^+W^- production at the LHC,” arXiv:1606.01034 [hep-ph].
- Dawson, S, Ian M. Lewis, and Mao Zeng (2013), “Threshold resummed and approximate next-to-next-to-leading order results for W^+W^- pair production at the LHC,” *Phys. Rev.* **D88** (5), 054028, arXiv:1307.3249.
- Degrande, C, *et al.* (2013a), “Studies of Vector Boson Scattering And Triboson Production with DELPHES Parametrized Fast Simulation for Snowmass 2013,” in *Community Summer Study 2013: Snowmass on the Mississippi (CSS2013) Minneapolis, MN, USA, July 29-August 6, 2013*, arXiv:1309.7452 [physics.comp-ph].
- Degrande, Celine, Oscar Éboli, Bastian Feigl, Barbara Jäger, Wolfgang Kilian, Olivier Mattelaer, Michael Rauch, Jürgen Reuter, Marco Sekulla, and Doreen Wackerroth (2013b), “Monte Carlo tools for studies of non-standard electroweak gauge boson interactions in multi-boson processes: A Snowmass White Paper,” in *Proceedings, Community Summer Study 2013: Snowmass on the Mississippi (CSS2013): Minneapolis, MN, USA, July 29-August 6, 2013*, arXiv:1309.7890 [hep-ph].
- Degrande, Celine, Nicolas Greiner, Wolfgang Kilian, Olivier Mattelaer, Harrison Mebane, Tim Stelzer, Scott Willenbrock, and Cen Zhang (2013c), “Effective Field Theory: A Modern Approach to Anomalous Couplings,” *Annals Phys.* **335**, 21–32, arXiv:1205.4231 [hep-ph].
- Denner, Ansgar, Stefan Dittmaier, Markus Hecht, and Christian Pasold (2015), “NLO QCD and electroweak corrections to $W + \gamma$ production with leptonic W-boson decays,” *JHEP* **04**, 018, arXiv:1412.7421 [hep-ph].
- Denner, Ansgar, Stefan Dittmaier, Markus Hecht, and Christian Pasold (2016), “NLO QCD and electroweak corrections to $Z + \gamma$ production with leptonic Z-boson decays,” *JHEP* **02**, 057, arXiv:1510.08742 [hep-ph].
- Dicus, D A, and V. S. Mathur (1973), “Upper bounds on the values of masses in unified gauge theories,” *Phys. Rev.* **D7**, 3111–3114.
- Éboli, O J P, and M. C. Gonzalez-Garcia (2004), “Probing trilinear gauge boson interactions via single electroweak gauge boson production at the CERN LHC,” *Phys. Rev.* **D70**, 074011, arXiv:hep-ph/0405269 [hep-ph].
- Éboli, O J P, M. C. Gonzalez-Garcia, and J. K. Mizukoshi (2006), “ $pp \rightarrow jje^\pm \mu^\pm \nu \nu$ and $jje^\pm \mu^\mp \nu \nu$ at $\mathcal{O}(\alpha_{\text{em}}^6)$ and $\mathcal{O}(\alpha_{\text{em}}^4 \alpha_s^2)$ for the Study of the Quartic Electroweak Gauge Boson Vertex at LHC,” *Phys. Rev.* **D74**, 073005, arXiv:hep-ph/0606118 [hep-ph].
- Éboli, O J P, and M. C. Gonzalez-Garcia (2016), “Classifying the bosonic quartic couplings,” *Phys. Rev.* **D93** (9), 093013, arXiv:1604.03555 [hep-ph].
- Éboli, Oscar J P, M. C. Gonzalez-Garcia, and S. F. Novaes (1994), “Quartic anomalous couplings in e gamma colliders,” *Nucl. Phys.* **B411**, 381–396, arXiv:hep-ph/9306306 [hep-ph].
- Ellis, John, Veronica Sanz, and Tevong You (2015), “The Effective Standard Model after LHC Run I,” *JHEP* **03**, 157, arXiv:1410.7703 [hep-ph].
- Evans, Lyndon, and Philip Bryant (2008), “LHC Machine,” *JINST* **3**, S08001.
- Falkowski, Adam, and Francesco Riva (2015), “Model-independent precision constraints on dimension-6 operators,” *JHEP* **02**, 039, arXiv:1411.0669 [hep-ph].
- Farhi, Edward, and Leonard Susskind (1981), “Technicolor,” *Phys. Rept.* **74**, 277.
- Frixione, Stefano, Paolo Nason, and Carlo Oleari (2007), “Matching NLO QCD computations with Parton Shower simulations: the POWHEG method,” *JHEP* **11**, 070, arXiv:0709.2092 [hep-ph].
- Frye, Christopher, Marat Freytsis, Jakub Scholtz, and Matthew J. Strassler (2016), “Precision Diboson Observables for the LHC,” *JHEP* **03**, 171, arXiv:1510.08451 [hep-ph].
- Gehrmann, T, M. Grazzini, S. Kallweit, P. Maierhöfer, A. von Manteuffel, S. Pozzorini, D. Rathlev, and L. Tancredi (2014), “ W^+W^- Production at Hadron Colliders in Next to Next to Leading Order QCD,” *Phys. Rev. Lett.* **113** (21), 212001, arXiv:1408.5243 [hep-ph].
- Georgi, Howard, and David B. Kaplan (1984), “Composite Higgs and Custodial SU(2),” *Phys. Lett.* **B145**, 216–220.
- Giudice, G F, C. Grojean, A. Pomarol, and R. Rattazzi (2007), “The Strongly-Interacting Light Higgs,” *JHEP* **06**, 045, arXiv:hep-ph/0703164 [hep-ph].
- Gleisberg, T, Stefan. Höche, F. Krauss, M. Schönherr, S. Schumann, *et al.* (2009), “Event generation with SHERPA 1.1,” *JHEP* **02**, 007, arXiv:0811.4622 [hep-ph].
- Gleisberg, Tanju, and Stefan Höche (2008), “Comix, a new matrix element generator,” *JHEP* **12**, 039, arXiv:0808.3674 [hep-ph].
- Gounaris, G, *et al.* (1996), “Triple gauge boson couplings,” in *AGS / RHIC Users Annual Meeting Upton, New York, June 15-16, 1995*, arXiv:hep-ph/9601233 [hep-ph].
- Gounaris, G J, J. Layssac, and F. M. Renard (2000), “New and standard physics contributions to anomalous Z and gamma selfcouplings,” *Phys. Rev.* **D62**, 073013, arXiv:hep-ph/0003143 [hep-ph].
- Grazzini, Massimiliano, Stefan Kallweit, Stefano Pozzorini, Dirk Rathlev, and Marius Wiesemann (2016a), “ W^+W^- production at the LHC: fiducial cross sections and distributions in NNLO QCD,” arXiv:1605.02716 [hep-ph].
- Grazzini, Massimiliano, Stefan Kallweit, and Dirk Rathlev (2015a), “ $W\gamma$ and $Z\gamma$ production at the LHC in NNLO QCD,” *JHEP* **07**, 085, arXiv:1504.01330 [hep-ph].
- Grazzini, Massimiliano, Stefan Kallweit, and Dirk Rathlev (2015b), “ZZ production at the LHC: fiducial cross sections

- and distributions in NNLO QCD,” Phys. Lett. **B750**, 407–410, arXiv:1507.06257 [hep-ph].
- Grazzini, Massimiliano, Stefan Kallweit, Dirk Rathlev, and Marius Wiesemann (2015c), “Transverse-momentum resummation for vector-boson pair production at NNLL+NNLO,” JHEP **08**, 154, arXiv:1507.02565 [hep-ph].
- Grazzini, Massimiliano, Stefan Kallweit, Dirk Rathlev, and Marius Wiesemann (2016b), “ $W^\pm Z$ production at hadron colliders in NNLO QCD,” arXiv:1604.08576 [hep-ph].
- Grzadkowski, B., M. Iskrzynski, M. Misiak, and J. Rosiek (2010), “Dimension-Six Terms in the Standard Model Lagrangian,” JHEP **10**, 085, arXiv:1008.4884 [hep-ph].
- Hagiwara, Kaoru, R. D. Peccei, D. Zeppenfeld, and K. Hikasa (1987), “Probing the Weak Boson Sector in $e^+e^- \rightarrow W^+W^-$,” Nucl. Phys. **B282**, 253–307.
- Höche, Stefan, Frank Krauss, Steffen Schumann, and Frank Siegert (2009), “QCD matrix elements and truncated showers,” JHEP **05**, 053, arXiv:0903.1219 [hep-ph].
- Jaiswal, Prerit, Karoline Kopp, and Takemichi Okui (2013), “Higgs Production Amidst the LHC Detector,” Phys. Rev. **D87** (11), 115017, arXiv:1303.1181 [hep-ph].
- Jaiswal, Prerit, Patrick Meade, and Harikrishnan Ramani (2016), “Precision diboson measurements and the interplay of pT and jet-veto resummations,” Phys. Rev. **D93** (9), 093007, arXiv:1509.07118 [hep-ph].
- Jaiswal, Prerit, and Takemichi Okui (2014), “Explanation of the WW excess at the LHC by jet-veto resummation,” Phys. Rev. **D90** (7), 073009, arXiv:1407.4537 [hep-ph].
- Kaplan, David B, and Howard Georgi (1984), “ $SU(2) \times U(1)$ Breaking by Vacuum Misalignment,” Phys. Lett. **B136**, 183–186.
- Khachatryan, Vardan, *et al.* (2014a), “Identification techniques for highly boosted W bosons that decay into hadrons,” JHEP **12**, 017, arXiv:1410.4227 [hep-ex].
- Khachatryan, Vardan, *et al.* (2014b), “Search for massive resonances decaying into pairs of boosted bosons in semi-leptonic final states at $\sqrt{s} = 8$ TeV,” JHEP **08**, 174, arXiv:1405.3447 [hep-ex].
- Khachatryan, Vardan, *et al.* (2015a), “Measurement of electroweak production of two jets in association with a Z boson in proton-proton collisions at $\sqrt{s} = 8$ TeV,” Eur. Phys. J. **C75** (2), 66, arXiv:1410.3153 [hep-ex].
- Khachatryan, Vardan, *et al.* (2015b), “Measurement of the $pp \rightarrow ZZ$ production cross section and constraints on anomalous triple gauge couplings in four-lepton final states at $\sqrt{s} = 8$ TeV,” Phys. Lett. **B740**, 250–272, arXiv:1406.0113 [hep-ex].
- Khachatryan, Vardan, *et al.* (2015c), “Measurement of the W^+W^- cross section in pp collisions at $\sqrt{s} = 8$ TeV and limits on anomalous gauge couplings,” arXiv:1507.03268 [hep-ex].
- Khachatryan, Vardan, *et al.* (2015d), “Measurement of the $Z\gamma$ production cross section in pp collisions at 8 TeV and search for anomalous triple gauge boson couplings,” JHEP **04**, 164, arXiv:1502.05664 [hep-ex].
- Khachatryan, Vardan, *et al.* (2015e), “Measurements of the ZZ production cross sections in the $2\ell 2\nu$ channel in proton-proton collisions at $\sqrt{s} = 7$ and 8 TeV and combined constraints on triple gauge couplings,” arXiv:1503.05467 [hep-ex].
- Khachatryan, Vardan, *et al.* (2015f), “Performance of Electron Reconstruction and Selection with the CMS Detector in Proton-Proton Collisions at $\sqrt{s} = 8$ TeV,” JINST **10** (06), P06005, arXiv:1502.02701 [physics.ins-det].
- Khachatryan, Vardan, *et al.* (2015g), “Performance of Photon Reconstruction and Identification with the CMS Detector in Proton-Proton Collisions at $\sqrt{s} = 8$ TeV,” JINST **10** (08), P08010, arXiv:1502.02702 [physics.ins-det].
- Khachatryan, Vardan, *et al.* (2015h), “Performance of the CMS missing transverse momentum reconstruction in pp data at $\sqrt{s} = 8$ TeV,” JINST **10** (02), P02006, arXiv:1411.0511 [physics.ins-det].
- Khachatryan, Vardan, *et al.* (2015i), “Study of vector boson scattering and search for new physics in events with two same-sign leptons and two jets,” Phys. Rev. Lett. **114** (5), 051801, arXiv:1410.6315 [hep-ex].
- Khachatryan, Vardan, *et al.* (2015j), *Technical Proposal for the Phase-II Upgrade of the CMS Detector*, Tech. Rep. CERN-LHCC-2015-010. LHCC-P-008 (CERN, Geneva. Geneva) upgrade Project Leader Deputies: Lucia Silvestris (INFN-Bari), Jeremy Mans (University of Minnesota) Additional contacts: Lucia.Silvestris@cern.ch, Jeremy.Mans@cern.ch.
- Khachatryan, Vardan, *et al.* (2016a), “Evidence for exclusive $\gamma\gamma \rightarrow W^+W^-$ production and constraints on anomalous quartic gauge couplings at $\sqrt{s} = 7$ and 8 TeV,” arXiv:1604.04464 [hep-ex].
- Khachatryan, Vardan, *et al.* (2016b), “Jet energy scale and resolution in the CMS experiment in pp collisions at 8 TeV,” arXiv:1607.03663 [hep-ex].
- Khachatryan, Vardan, *et al.* (2016c), “Measurement of electroweak production of a W boson and two forward jets in proton-proton collisions at $\sqrt{s} = 8$ TeV,” arXiv:1607.06975 [hep-ex].
- Khachatryan, Vardan, *et al.* (2016d), “Measurement of the $Z\gamma \rightarrow \nu\bar{\nu}\gamma$ production cross section in pp collisions at $\sqrt{s} = 8$ TeV and limits on anomalous $ZZ\gamma$ and $Z\gamma\gamma$ trilinear gauge boson couplings,” arXiv:1602.07152 [hep-ex].
- Khachatryan, Vardan, *et al.* (2016e), “Measurement of the WZ production cross section in pp collisions at $\sqrt{s} = 7$ and 8 TeV and search for anomalous triple gauge couplings at $\sqrt{s} = 8$ TeV,” arXiv:1609.05721 [hep-ex].
- Khachatryan, Vardan, *et al.* (2016f), “The CMS trigger system,” arXiv:1609.02366 [physics.ins-det].
- Kilian, Wolfgang, Thorsten Ohl, Juergen Reuter, and Marco Sekulla (2015), “High-Energy Vector Boson Scattering after the Higgs Discovery,” Phys. Rev. **D91**, 096007, arXiv:1408.6207 [hep-ph].
- Kotwal, Ashutosh V, Heidi Schellman, and Jadranka Sekaric (2015), “Review of Physics Results from the Tevatron: Electroweak Physics,” Int. J. Mod. Phys. **A30** (06), 1541004, arXiv:1409.5163 [hep-ex].
- Lampl, W, S. Laplace, D. Lelas, P. Loch, H. Ma, S. Menke, S. Rajagopalan, D. Rousseau, S. Snyder, and G. Unal (2008), “Calorimeter clustering algorithms: Description and performance,” .
- Lazopoulos, Achilleas, Kirill Melnikov, and Frank Petriello (2007), “QCD corrections to tri-boson production,” Phys. Rev. **D76**, 014001, arXiv:hep-ph/0703273 [hep-ph].
- Lee, Benjamin W, C. Quigg, and H. B. Thacker (1977), “The Strength of Weak Interactions at Very High-Energies and the Higgs Boson Mass,” Phys. Rev. Lett. **38**, 883–885.
- Liu, Da, Alex Pomarol, Riccardo Rattazzi, and Francesco Riva (2016), “Patterns of Strong Coupling for LHC Searches,” arXiv:1603.03064 [hep-ph].
- Llewellyn Smith, C H (1973), “High-Energy Behavior and Gauge Symmetry,” Phys. Lett. **B46**, 233–236.

- Longhitano, Anthony C (1980), “Heavy Higgs Bosons in the Weinberg-Salam Model,” *Phys. Rev.* **D22**, 1166.
- Longhitano, Anthony C (1981), “Low-Energy Impact of a Heavy Higgs Boson Sector,” *Nucl. Phys.* **B188**, 118–154.
- Mangano, Michelangelo L, *et al.* (2003), “ALPGEN, a generator for hard multiparton processes in hadronic collisions,” *JHEP* **07**, 001, arXiv:hep-ph/0206293 [hep-ph].
- Meade, Patrick, Harikrishnan Ramani, and Mao Zeng (2014), “Transverse momentum resummation effects in W^+W^- measurements,” *Phys. Rev.* **D90** (11), 114006, arXiv:1407.4481 [hep-ph].
- Melia, Tom, Paolo Nason, Raoul Rontsch, and Giulia Zanderighi (2011), “ $W+W^-$, WZ and ZZ production in the POWHEG BOX,” *JHEP* **11**, 078, arXiv:1107.5051 [hep-ph].
- Nason, Paolo (2004), “A New method for combining NLO QCD with shower Monte Carlo algorithms,” *JHEP* **11**, 040, arXiv:hep-ph/0409146 [hep-ph].
- Nason, Paolo, and Giulia Zanderighi (2014), “ W^+W^- , WZ and ZZ production in the POWHEG-BOX-V2,” *Eur. Phys. J.* **C74** (1), 2702, arXiv:1311.1365 [hep-ph].
- Pomarol, Alex, and Francesco Riva (2014), “Towards the Ultimate SM Fit to Close in on Higgs Physics,” *JHEP* **01**, 151, arXiv:1308.2803 [hep-ph].
- Rauch, Michael (2016), “Vector-Boson Fusion and Vector-Boson Scattering,” .
- Reuter, J, Wolfgang Kilian, and Marco Sekulla (2013), “Simplified Models for New Physics in Vector Boson Scattering - Input for Snowmass 2013,” arXiv:1307.8170 [hep-ph].
- Ritz, Steve, *et al.* (2014), “Building for Discovery: Strategic Plan for U.S. Particle Physics in the Global Context,” .
- Rolbiecki, Krzysztof, and Kazuki Sakurai (2013), “Light stops emerging in WW cross section measurements?” *JHEP* **09**, 004, arXiv:1303.5696 [hep-ph].
- Schael, S, *et al.* (2013), “Electroweak Measurements in Electron-Positron Collisions at W-Boson-Pair Energies at LEP,” *Phys. Rept.* **532**, 119–244, arXiv:1302.3415 [hep-ex].
- Schumann, Steffen, and Frank Krauss (2008), “A Parton shower algorithm based on Catani-Seymour dipole factorisation,” *JHEP* **03**, 038, arXiv:0709.1027 [hep-ph].
- Searcy, Jacob, Lillian Huang, Marc-André Pleier, and Junjie Zhu (2015), “Determination of the WW polarization fractions in $pp \rightarrow W^\pm W^\pm jj$ using a deep machine learning technique,” arXiv:1510.01691 [hep-ph].
- Sekulla, Marco, Wolfgang Kilian, Thorsten Ohl, and Jürgen Reuter (2016), “Effective Field Theory and Unitarity in Vector Boson Scattering,” in *Proceedings, Fourth Annual Large Hadron Collider Physics, 13-18 June 2016, Lund, Sweden*, arXiv:1610.04131 [hep-ph].
- Stirling, W James, and Anja Werthenbach (2000), “Anomalous quartic couplings in $W^+W^-\gamma$, $Z^0Z^0\gamma$ and $Z^0\gamma\gamma$ production at present and future e^+e^- colliders,” *Eur. Phys. J.* **C14**, 103–110, arXiv:hep-ph/9903315 [hep-ph].
- Susskind, Leonard (1979), “Dynamics of Spontaneous Symmetry Breaking in the Weinberg-Salam Theory,” *Phys. Rev.* **D20**, 2619–2625.
- Wang, Yan, Chong Sheng Li, Ze Long Liu, Ding Yu Shao, and Hai Tao Li (2013), “Transverse-Momentum Resummation for Gauge Boson Pair Production at the Hadron Collider,” *Phys. Rev.* **D88**, 114017, arXiv:1307.7520.
- Weinberg, Steven (1976), “Implications of Dynamical Symmetry Breaking,” *Phys. Rev.* **D13**, 974–996.
- Wiesemann, Marius, Massimiliano Grazzini, Stefan Kallweit, and Dirk Rathlev (2016), “MATRIX: A fully-differential NNLO(+NNLL) process library,” *Proceedings, 13th DESY Workshop on Elementary Particle Physics: Loops and Legs in Quantum Field Theory (LL2016): Leipzig, Germany, April 24-29, 2016*, PoS **LL2016**, 072.
- Yong-Bai, Shen, Zhang Ren-You, Ma Wen-Gan, Li Xiao-Zhou, and Guo Lei (2016), “NLO QCD + EW corrections to WWW production with leptonic decays at the LHC,” arXiv:1605.00554 [hep-ph].
- Yong-Bai, Shen, Zhang Ren-You, Ma Wen-Gan, Li Xiao-Zhou, Zhang Yu, and Guo Lei (2015), “NLO QCD + NLO EW corrections to WZZ productions with leptonic decays at the LHC,” *JHEP* **10**, 186, arXiv:1507.03693 [hep-ph].